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STANDARDIZED SPECIFICATIONS FOR SILICON  
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DEVELOPMENT OF STANDARDIZED SPECIFICATIONS  
FOR SILICON SOLAR CELLS

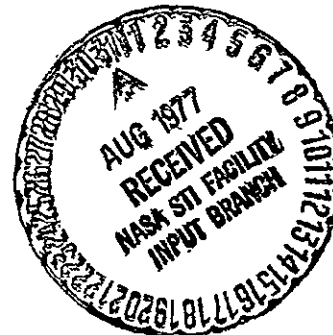
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16 Abstract A space silicon solar cell assembly (cell and coverglass) specification aimed at standardizing the diverse requirements of current cell or assembly specifications was developed for potential use by all NASA agencies. This specification was designed to minimize both the procurement and manufacturing costs for space qualified silicon solar cell assemblies. The document generated by this contract represents a consensus opinion of cell users, manufacturers and government agencies directly involved in the management of space vehicle programs.  In addition, an impact analysis estimating the technological and economic effects of employing a standardized space silicon solar cell assembly was performed by Spectrolab and the Pepperdine Research Institute.					
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## I. SUMMARY

A space silicon solar cell assembly (cell and coverglass) specification aimed at standardizing the diverse requirements of current cell or assembly specifications was developed for potential use by all NASA agencies. This specification was designed to minimize both the procurement and manufacturing costs for space qualified silicon solar cell assemblies. The document generated by this contract represents a consensus opinion of cell users, manufacturers and government agencies directly involved in the management of space vehicle programs. A great deal of contract direction was derived from periodic reviews of this program performed by the Ad Hoc Team for Solar Cell Standardization, which consisted of representatives of both NASA and the Department of Defense.

The specification that resulted evolved from an initial review and collation of current representative specifications that in turn led to the development of a questionnaire which was used as a vehicle to survey the preferences of those organizations directly or indirectly involved in space silicon solar cell or assembly utilization. The results of the survey were used to derive a tentative standardized space silicon solar cell assembly specification. This document was reviewed and modified by the Ad Hoc Team and presented at the Solar Cell Specification Workshop for further review by the industry. In addition, an impact analysis estimating the technological and economic effects of employing a standardized space silicon solar cell assembly was performed by Spectrolab and the Pepperdine Research Institute. The version of the specification as presented at the Workshop is included as an Appendix to this report. Further modifications are anticipated, however, before final implementation by NASA.

## II. INTRODUCTION

From the inception of the space program nearly every spacecraft has been custom made for the particular mission application. Initially such an approach was not a dominant factor in long term planning. However the growth of the unmanned space program has now reached the stage where cost is a prime consideration. As part of an overall effort to reduce mission cost, NASA has begun to examine standardizing spacecraft components and subsystems as a possible cost reduction method.

The purpose of this particular program is to attempt to develop a set of standardized specifications to be used for space silicon solar cell procurements. These particular components have provided the main source of power for most unmanned space missions. As part of this effort it was necessary to judge the viability of the basic concept of cell standardization and also assess the economic and technological ramifications of this approach to space silicon solar cell procurement.

The specification contained in the Appendix of this report is the result of a methodology that began with a review of present specifications, followed by an industry-wide survey which included various government agencies. From the data obtained, a tentative specification for a space silicon solar cell assembly (solar cell and coverglass), was developed. This initial document was critiqued and revised with the assistance of the Ad Hoc Team for Solar Cell Standardization.\*

In parallel with this phase of the program, a cost benefits analysis was performed by an independent organization (Pepperdine Research Institute) to assess the economic impact of cell standardization. Both efforts were combined and presented to the industry for review at the Solar Cell Specification Workshop held in Cleveland during August 1976. Following this review, a revised version of the specification was generated by the Ad Hoc Team for Solar Cell Standardization for further review by industry. Additional revisions after NASA review are anticipated prior to adoption and implementation.

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### III. REVIEW AND COLLATION OF EXISTING SPECIFICATIONS

The first step in the process of developing a set of standardized specifications for space silicon solar cells, was to review the current specifications that were being generated by those organizations procuring solar cells. Documents developed by government agencies such as NASA and the Department of Defense, as well as private organizations were examined. In many cases more than one specification of a particular organization was examined for the purpose of assessing the impact of new solar cell technology upon their requirements. In all thirty-three (33) specifications representing eighteen (18) organizations were examined. Table 1 lists those organizations represented in the review phase.

Although there are many government agencies and private companies that can be technically classified as solar cell users, it appeared that for all practical purposes only those organizations that are directly involved in solar panel fabrication generated complete solar cell specifications. This situation occurs since the panel must conform to the overall system configuration of the vehicle, and in most cases the prime contractor is not directly involved in this particular subsystem.

From a systems aspect the panel is determined by the amount of area available, the power required, the weight allowed and the environment that must be experienced. Provided that the panel envelope characteristics are not compromised, the decisions concerning the details of achieving these goals are usually left to the panel supplier. As mentioned previously, the panel supplier is in many cases not affiliated in any way with the prime contractor.

At present in the United States there are six organizations directly involved in the manufacture of solar cell panels, four of these groups can be defined as affiliated directly with prime contractors, while the other two are independent suppliers. This suggested that the survey which was to be undertaken during this contract could be reduced in scope to concentrate only on these six groups plus qualified representatives of NASA and the Department of Defense. However it was decided after consultation with the Ad Hoc Team for Solar Cell Standardization (AHTSCS) that it would be more prudent to include a wider spectrum of organizations in the survey phase of this contract.

A preliminary review of the sample specifications revealed a number of significant trends in solar cell specifications. Three years ago nearly all cells could be categorized as (1) between 0.25 to 0.40mm in thickness, (2) nominal 2 or nominal 10 ohm cm in resistivity, (3) 2 x 2 cm in geometry, (4) soldered silver-titanium contacts, (5) a contact configuration featuring 3 grids per cm terminating at an ohmic bar ~ 1.0mm wide and (6) a power output of ~ 10 to 11 percent AMO, the higher end for the lower resistivity cells being procured.

Table 1

## Specifications Reviewed

<u>Organization</u>	<u>Dated</u>
Applied Physics Lab., Johns Hopkins University	June 1973 May 1975
Aeronutronic Ford - WDL	June 1972 May 1973 Aug 1974
Ball Brothers Research Corp.	July 1975
Boeing Company	Oct 1972 Nov 1974
General Dynamics-Convair Division	Oct 1974
General Electric Company	Oct 1974 Jan 1975
Hughes Aircraft Company	Sept 1972 Mar 1975 July 1975
Lincoln Laboratory - M.I.T.	Dec 1968
Lockheed Missiles and Space Company	Nov 1973 Mar 1974 Sept 1974
Martin-Marietta Corp.	Sept 1974
McDonnell-Douglas Corp.	Nov 1974
NASA-Goddard Space Flight Center	Sept 1974 Aug 1975
Naval Research Laboratory	May 1973
RCA-Astro-Electronics Division	Apr 1974 Nov 1974
Rockwell International - Space Division	Oct 1973
Spectrolab Incorporated	Apr 1973 Aug 1973 Apr 1975
TRW Systems Group	Apr 1973 May 1974 July 1974
Wright-Patterson Air Force Base	Apr 1974



Recent specifications have extended the thickness range to include 0.20mm cells, the resistivity range to include 45 ohm cm material, called out passivated (palladium added) contact systems that are not solder covered, required up to 12 grids per cm, reduced the ohmic bar to 0.5mm in width, included pads on the ohmic bar, changed cell geometry to such extremes as 2.1 cm x 3.8 cm, increased cell size to 2.2 x 6.2 cm, and of even more critical importance now required efficiencies up to nearly 13 percent AMO. These changes have been mandated by vehicle design constraints; the panel must conform to the requirements of the vehicle. Thus the components of the panel, the cells and covers, have dramatically changed.

Many specifications were now composed of two sections, the main specification which set out the basic requirements, and a separate specification work sheet that precisely defined the limits of acceptability. In view of the fact that there are now at least three types of cells; traditional, hybrid or violet, and field; this approach is logical.

There were now more specifications addressing the total cell assembly, namely the solar cell and the filter. This may be a cost effective method for procuring cells and covers since it removes a major uncertainty, filtered power performance, and all those requirements that were of necessity incorporated in order to assure proper filtered performance.

A third trend was a new class of specifications that deal with advanced solar cells, and of even more importance, advanced methods of interconnecting them (welding). Since the cell user, in most cases, is technically more advanced in such matters as welding, there may be a potential problem in translating this technology to the cell producer in order that these new cells may be adequately tested.

The final trend was the inclusion of new requirements and in some cases the escalation of former requirements to more stringent levels. Some of this is a reflection of a more mature understanding of the solar cell, but in many cases the new requirements seem to be reactions to problems that have never been satisfactorily resolved. This trend leads to lower cell yields and associated increases in cell cost.

These changes seemed to argue against an attempt to rigidly define a standard cell. However the changes that are occurring do not in most cases have any significant impact on tolerances, methods of assuring reliability or the general quality of the solar cell itself. Therefore the initial view on standardization was to concentrate on these common aspects of solar cells.

It was apparent that the format used for all specifications is the same, regardless of the organization that generates the document. The main sections of the typical solar cell specification are as follows: (1) scope, (2) applicable documents, (3) requirements, (4) quality assurance provisions, (5) preparation for delivery and (6) notes.

The section devoted to "Scope" was in almost all cases extremely brief and confined to a statement describing the purpose of the specification document. In a few specifications the Scope section contained instructions or information that in a technical sense should be in either the "applicable document" or "requirements" section.

The second section devoted to Applicable Documents did not present the same degree of commonality. Table 2 lists the various government documents called out by each organization. These specifications call out twenty-six different applicable documents and in no case is any single document common to all specifications. There are only three documents that are called out in more than twenty-five percent of the specifications.

Interestingly enough the various applicable documents seemed to have little, if any impact on the actual manufacturing, testing or delivery of the solar cells. Since there did not seem to be any correlation between the number and types of applicable government documents and the cell produced, the question of the need and usefulness of this section was included in the subsequent questionnaire.

A review of the Requirements section of the chosen specifications showed a trend toward more requirements. The format for this section was not common, but basically all requirements fell into three general categories: descriptive, operational and control. A descriptive requirement is one which defines or limits the configuration and materials which comprise the solar cell; e.g. "the contact material shall be sintered titanium-silver." An operational requirement is one which defines any performance characteristic of the cell or any element of the cell; e.g. "when tape tested there shall be no evidence of contact peeling or delamination." A control requirement is one which defines the responsibilities of the manufacturer in the production or testing of the cell; e.g. "all cells shall be tape tested using Scotch Brand #500 transparent tape."

#### A. Descriptive Requirements

A solar cell can be broken down into a few key elements; the starting (bulk) material, the diffused junction, the contacts, the antireflection coating and in many cases, the solder applied to the contacts to allow cell interconnections. Each of these elements was examined with respect to descriptive requirements, and a listing of all requirements for each element was compiled and presented in Table 3. In many cases the requirement is implied by some other statement; e.g. blank squareness is mandated in some specifications by requiring that the cell shall be capable of sitting flat in a square whose sides are slightly larger than the upper limit of the outside dimensions required.

The first two entries under bulk material are fairly evident and are usually described by a brief sentence in a paragraph entitled "Type." The resistivity range is sometimes called out in the main body of the specification, but it also may be listed in a separate specification work sheet,

Table 2 Applicable Documents

<u>Document Title</u>	<u>Identification Number</u>	<u>Frequency Used</u>
Optical Components for Fire Control Instruments	MIL-O-13830	.06
Coating of Glass Optical Elements	MIL-C-675A	.06
Solder; Lead Alloy	QQ-S-571	.44
Specification for Determining Relative 1 MeV Electron Radiation Damage Resistance for Silicon Solar Cells	NAS63-106	.25
Tapes, Packaging, Adhesive and Gummed, Method of Inspection, Sampling and Testing	FED Standard 147	.44
Sampling, Procedures and Tables for Inspection by Attributes	MIL-STD-105D	.50
Eraser, Rubber-Pumice for Testing Coated Optical Elements	MIL-E-12397	.06
Dissimilar Metals	MIL-STD-889	.06
Standards and Specifications, Order of Precedence for the Selection of	MIL-STD-143B	.19
Desiccants, Activated, Bagged Packing Use and Static Dehumidification	MIL-S-3464	.25
Semiconductor Devices, General Specification for	MIL-S-19500	.25
Film Transparent, Flexible, Heat Sealable; for Packaging Applications	MIL-F-22191	.25
Environment Test Methods	MIL-STD-810B	.06
Photovoltaic Solar Simulator Specification	AIEE	.06
NASA Space Vehicle Design Criteria	NASA SP-8005	.06
The Solar Constant, F. S. Johnson J. Meteorology, 11 pp. 431-439		.12
Quality Program Requirements	NASA NHB 5300.4(1c)	.19
Quality Program Requirements	MIL-Q-9858A	.25
Inspection System Provisions for Suppliers of Space Materials, Parts Components and Services	NPC-200-3	.06

Table 2 (cont'd)

<u>Document Title</u>	<u>Identification Number</u>	<u>Frequency Used</u>
Contractor Parts Control and Standard Program	MIL-STD-891A	.06
Tin Plating, Electro Deposited on Hot Dipped for Ferrous and Nonferrous Metals	MIL-T-10727	.06
Copper, Flat Products	QQ-C-576	.06
Calibration System Requirements	MIL-C-45662A	.19
Inspection Systems Requirements	MIL-I-45208A	.12
Quality Program Provisions for Aeronautical and Space System Contractors	NHB5300.4(1B)	.06
Requirements for Soldered Electrical Connections	NHB5300.4(3A)	.06

Table 3 Major Descriptive Requirements

<u>Element</u>	<u>Comments</u>
Type	P-type in all cases
Dopant	Sometimes specified, always boron
Orientation	Specified rarely, (100) orientation is industry standard
Growth Method	Never specified, crucible grown is industry standard
Dislocation Density	Importance not known, information only
Oxygen Content	See above
Mobility	See above
Minority Carrier Lifetime	See above
Resistivity	Nominal 2 or nominal 10 ohm cm
Outside Dimensions	Considerable variation in tolerances ranging from $\pm .05\text{mm}(.002")$ to $\pm .13\text{mm}(.005")$
Thickness	Determined by desired final weight, tolerance range generally $\pm .05\text{mm}$
Weight	Determined by silicon and solder thickness requirements
Squareness	Important for filtering and panel laydown, can increase cell cost in extreme cases
Scratches	Subjective criterion
Nicks	Not adequately defined in some specifications
Cracks	Always forbidden
Corner Chips	Allowances seem arbitrary
Edge Chips	Allowances seem arbitrary; not properly scaled for varying cell sizes
Junction Dopant	Sometimes defined, controlled by required documentation in other cases
Depth	Vague reference to "shallow"
Location	Junction on cell edges of great concern

Table 3 (cont'd)

Element	<u>Comments</u>
Contact Material	Defined in all specifications, titanium-silver or titanium-palladium-silver
Location	Zero gap or float
Configuration	Some trend towards pads rather than collector bars, needless instructions on grid design
Thickness	New requirement fostered by welding
Defects	Wide variation in allowances
Antireflection Material	Usually defined
Index of Refraction	Not addressed
Optical Thickness	Addressed obliquely
Coverage	Handled adequately in majority of specifications
Defects	Most subjective of all requirements
Solder Material	Composition carefully specified, some variation from user to user
Coverage	Usually given in terms of percent to be covered, extremely tight tolerances in certain defined areas
Defects	Voids, dewetting are main concerns
Thickness	Extremely wide tolerance, almost always determined by weight

or as an entry in the cell drawing. Almost all specification packages contain a cell drawing, some quite detailed. There are basically two resistivity ranges called out; nominal two ohm-cm which is defined as silicon from one to three ohm-cm, and nominal ten ohm-cm which ranges from as low as six ohm-cm to as high as fifteen ohm-cm. The amount of variation in resistivity range from specification to specification is minimal.

The physical dimensions of the finished cell; length, width, and thickness are not defined in a straightforward fashion in some specifications. If the cell is to be delivered unglazed, the length and width requirements are meaningful. However, if the cell is to be delivered in the glazed condition, then the total assembly dimensions will control the cell dimensions. The tolerance for length and width varies from  $\pm .05\text{mm}$  (.002") to  $\pm .13\text{mm}$  (.005"). The tolerance required has a definite influence on cell cost; the more stringent tolerance adds to the cost of the cell due to a lower yield in material of acceptable dimensions. The tolerance for cell thickness in almost all cases is  $\pm .05\text{mm}$  (.002"), although a few specifications require  $\pm .02\text{mm}$  (.001"). In this case the tighter tolerance on thickness will have a major impact on cost.

Actually the thickness specified is primarily determined by the weight requirement of the cell. This is especially true in the case where a soldered cell or a soldered cell with coverglass is the end product. It is possible in many instances to meet the weight requirements of a specification with cells that are at or above the upper limit of the thickness tolerance. Since the power output of the cell increases with increasing thickness, it is to the advantage of the manufacturer to work with a maximum thickness silicon blank. This suggests that thickness limits should be specified only in terms of a maximum, rather than by a range.

The weight requirement is usually given as the total weight of a fixed number of cells, or the average weight of a selected random sampling of cells in a shipping lot. This weight is the sum of the weight of the silicon blank, the contacts, and the solder; naturally for a weldable cell the last item is not included. From this viewpoint it might be more practical to completely eliminate thickness as a requirement and replace it by a weight only requirement. This idea was incorporated into the questionnaire.

In approximately fifty percent of the specifications the dopant to be used to obtain the particular silicon resistivity is identified. In all cases it is boron. Technically it is possible to dope silicon with alternate acceptors such as aluminum, indium or gallium, but this would be unlikely since boron is the most controllable dopant available.

There are a great number of rather important physical parameters for silicon that are rarely addressed in typical specifications, such as crystal orientation, dislocation density, oxygen content, mobility, and minority carrier lifetime. However, to attempt to categorize each ingot with respect to the above mentioned parameters would be extremely expensive and the benefits obtained from such knowledge are presently unknown.

A new requirement fostered by the interest in welded solar cells is surface finish. A number of specifications are now requiring that the cell blank be extremely smooth, 75 to 150 nanometer rms maximum being typical values for surface finishes. The impact on manufacturing costs has not been thoroughly assessed at this point, but it may require certain process changes that could influence yield negatively, thus increasing cost.

The last set of descriptive requirements, defects, for bulk material is generally exercised after the cell is fabricated, but technically they are placed on the starting material. These include nicks, scratches, cracks and chips. The scratch requirement is the most subjective; precise definition of what is acceptable is usually addressed by means of approved samples being set up by the manufacturer for use as standards in acceptance testing. Chips are defined and limited with a great deal of preciseness. For a 2 x 2 cm cell the edge chip is limited to 1.5mm x 3.8mm (.060" x .150"). However, for larger cells such as 2 x 4 and 2 x 6 cm, the edge chip requirements do not increase proportionately. Some attempts are made to compensate for the greater edge of the larger cell, but in these cases the allowable chip length does not increase in a linear fashion. For example 1.5 x 3.8mm for a 2 x 2 cm cell (on all edges) reasonably might be changed to 1.5 x 7.6mm for the 4 cm side of a 2 x 4 cm cell. The corner chip criterion varies from 1.5mm (.060") to 1.9mm (.075") on the hypotenuse for a 2 x 2 cm cell and the most generous allowance for a larger cell (2 x 4 to 2 x 6 cm) is 2.0mm (.080"). The reasoning for arriving at these particular numbers was not apparent.

Nicks are sometimes defined and specified in the same manner as chips. However many specifications arbitrarily combine nicks and scratches into a general category and treat them in the same subjective manner as scratches. Cracks in the cell are without exception forbidden.

The cell junction is usually addressed in a very superficial way. Very few specifications even call out what dopant should be used to form the junction. Many specifications allude to junction depth with a descriptive statement to the effect that "the cell shall be a shallow diffused, etc." The term "shallow" is at best imprecise. However, a precise requirement for junction depth would be very difficult to reliably verify and most definitely would add to cell cost. There is one requirement on the junction that now appears in almost all specifications. The absence of junction on the cell edges is now clearly a common requirement. This is to prevent electrical degradation caused by low energy protons which has been shown to be quite severe if any portion of the junction is not protected by a cover-slide. There are certain problems associated with verifying this requirement, but this will be discussed in the section pertaining to Quality Assurance Requirements.



All specifications attempt to identify the materials to be used for contacts; in all cases it is either titanium-silver or titanium-palladium-silver. A few specifications make statements concerning the purity of the silver. The contact configuration is determined by the cell drawing and until recently (1974), most configurations featured equally spaced grids terminating at a collector bar located on the long edge of the cell. The width of the gridlines is not usually specified, but the dimensions of the collector bar are carefully defined. Recently new types of configurations have been designed. In order to gain more active area the collector bar is being located on the short side of the cell. Newer designs now require contact pads connected by very narrow metal strips instead of the full width collector, in order to increase active area.

The location of the collector bar with respect to the cell edge seems to be a very important consideration. Approximately fifty percent of the specifications reviewed desire a zero gap condition, i.e. there is no active junction between the edge of the cell and the collector bar. This relates back to the concern about low energy proton degradation. Evidently some panel builders do not depend on a final conformal coating to protect exposed portions of the cell from radiation. The remaining specifications do allow a "float" or gap between the edge of the cell and the collector bar.

Since many cell users perform their own coverglassing it is critical that the inside of the collector bar be very accurately referenced to the cell edge. In addition it is vital that the width of the bar be sufficient to allow interconnects to be attached. This particular set of requirements often has a major impact on yield due to the limitations of cell contact tooling tolerances. Those performing cell glassing do not necessarily use common tooling and techniques, thus creating relatively large variances in required tolerances with associated wide variance in cell yield.

Another new requirement now being imposed is contact metallization thickness for welded cells. It has not been clearly established that such requirements are necessary, nor have the limits been accurately established. However, this requirement can be addressed in a standard specification provided the concept of a specification work sheet is used.

The final descriptive requirement pertaining to contacts concerns defects such as gridline discontinuities, voids, uncoated areas, pinholes and the like. There is a tremendous difference in requirements. Many specifications require that a fixed percentage of the potential contact area be metallized. Others are quite stringent with respect to voids and pinholes. What is acceptable to one cell user is a reject for another, thus leading to significant variations in cell price for cells that are basically manufactured under the same conditions using identical processes.

Antireflection requirements follow the same pattern of descriptive requirements, although some specifications merely state that an antireflective (AR) coating may be used. No specification addresses the most critical controlling parameter for AR coatings, the index of refraction.

Some specifications clearly define areas of the cell that may not be AR coated, such as the contact areas. Others depend on the solder coverage requirements to handle this requirement. The AR defects requirement of most specifications is the most subjective area of descriptive requirements. The "color and finish" standards that are derived should not in most cases have any meaning provided the cell delivers the required power output. Minor variations in optical thickness can show up as color changes in the coating ranging from violet to a very pale blue. These variations may detract from cosmetic requirements, but they are usually in no way indicative of any latent defect in the cell. Another subjective requirement is "stains" which are sometimes interpreted to mean that there is a potential defect in the cell. Generally stains are the result of variations in cell cleaning and all cells can be shown to possess stains. Defining what constitutes an acceptable stain is generally an arbitrary judgement based on a particular set of subjective evaluations. Other classes of defects such as voids, pinholes and blisters are in most cases defined with some degree of accuracy, but again they may be unnecessary if proper in-process or acceptance tests can be derived.

The final group of descriptive requirements deal with solder. The requirements fall into the categories of material, coverage, defects and thickness. The solder composition is mandated, with some variation in silver content from user to user. Coverage is usually given as a percentage of the contact area with more specific requirements described for certain critical areas of the cell. Defects such as voids, dewetted areas, and the like are usually precisely defined. Solder thickness requirements are usually given either as a maximum allowed thickness, or as a minimum-maximum range. In the latter case the range may cover an order of magnitude in thickness.

#### B. Operational Requirements

Table 4 is a list of all requirements classified as operational. There is a tremendous variation in both the number and types of operational requirements. In general the operational requirements reflect concern over the cell's ability to perform under the particular mission environments envisioned by the panel maker. Even though there are some common operational requirements such as electrical output and contact strength, there are very few common limits.

An examination of electrical output requirements indicates that all cells are required to deliver power at a given fixed voltage at a specific temperature under air mass zero conditions. Taking a nominal two ohm cm cell as an example, the voltage point can vary from a minimum of 460 mV to a maximum of 485 mV. The measurement temperature is anywhere from 25 to 30°C. Also, although the value for air mass zero in some cases varies from customer to customer, all claim that their particular standard solar cell accurately represents air mass zero conditions.

Table 4 Operational Requirements

<u>Element</u>	<u>Comments</u>
Electrical Output	Wide variation in test conditions; three classes of cells now being specified, minimum acceptable cell has impact on cost
Output After Glassing	Cost could be reduced by verifying AR coating index of refraction rather than glassing cells using techniques not similar to standard glassing practices
Radiation Resistance	No adequate documented reference available as standard
Radiometric Properties	Very important, but adequate facilities for test verification not available at vendor's facility
Spectral Response	Recent new requirement that is extremely important and needs to be standardized
Tape Peel	Type of tape to be used not standardized
15 Pull Strength	Wide variation in method of performance and acceptable minimum
Storage	Sometimes unrealistic, redundant with respect to humidity
Temperature-Humidity	Common requirement, but conditions of test vary
AR Coating Durability	Basic test involves exposure to water or steam followed by either tape or rub
High Temperature- Vacuum	Generally 1 week at 140°C under $1 \times 10^{-5}$ Torr for soldered cells
Temperature Cycling	Wide variation in number of cycles and temperature extremes, concern is for contact strength and electrical properties

The absolute power requirements naturally vary as a function of the cell's resistivity, thickness, active area and antireflection coating. The advent of advanced cell types has created a wide divergence in power requirements even for cells of the same resistivity and thickness. Any attempts to standardize cell power output must consider as a minimum three distinct types of cells; 1) the traditional or conventional assembly featuring a simple contact configuration, a comparatively deep diffusion, a silicon monoxide antireflection coating and a UV rejection filter that cuts on at 410 nm, 2) the hybrid or violet cell assembly which has a very sophisticated contact pattern (more grids, narrow collector bars or pads) a comparatively shallow diffusion, a high index antireflection coating such as tantalum pentoxide and a UV rejection filter cutting on at 350 nm, 3) the field cell assembly which possesses all the features of the hybrid type and also incorporates a back surface field that significantly increases the output power, especially for thin (.020 cm) solar cells. Any standardized power figure must be referenced in terms of the cell type.

Some specifications place additional requirements on the electrical output. For example a number of specifications require that the open circuit voltage be a minimum value regardless of the power at load. Other specifications require two load points be satisfied. Still others call out a fixed current and limit the voltage at which this current may be obtained.

There is some variation between the minimum output acceptable as opposed to the minimum average output required. Naturally the tighter the distribution (the smaller the variation allowed) the more costly the cell. The differential between the minimum and minimum average cell output ranges from three to nearly ten percent in the specifications reviewed.

Some specifications that call for unglassed cells do address the problem of glassing changes. To verify that the cells, when glassed, will deliver the needed power can be costly. This is an extremely strong argument for procuring glassed cells, since the uncertainty in final output is eliminated. At present some specifications require a significant sample of cells be tested with temporary glasses to verify the glassed output requirements. In the case of silicon monoxide AR coated cells, up to four percent degradation in output on a single cell is allowed, with the average reduction in power limited to three percent. With the new higher index materials there should be an appreciation in power and those addressing this aspect are developing extremely costly requirements. For example one specification requires that ten percent of all cells delivered be tested for glassing gains. It states that if any cell tested fails to meet a minimum percentage gain, then all cells from that lot shall be tested. Such requirements significantly increase the cell price and it is doubtful if they contribute to overall cost effectiveness with respect to filtered cells since the actual glassing operation is done quite differently. Such problems might be avoided if the specification required that the AR coating's index of refraction be verified since this particular optical property is the determining factor in glassing appreciation or degradation.

The behavior of the cell under radiation conditions is another important consideration, but one which is rarely verified in practice. Many users rely on rather outdated information in defining their particular requirements. The NASA generated document NAS63-106 issued in 1963 is referenced by some cell users, but the newer, more radiation resistant cells now being supplied have made this document nearly obsolete. Those organizations which do not employ NAS63-106 either rely on their own internally generated data, use published data which may not be particularly germane, or in some cases do not address the subject. This strongly suggests that an appropriate government agency be assigned the task of either updating the present radiation effects specification or developing a new document that can be used with confidence by the industry.

Radiometric requirements are included in many specifications since the absorptance and emittance of the assembly is a determining factor in the actual operating temperature of the cell. Although this is called out as a requirement, in practice this important parameter is rarely, if ever, measured by the cell manufacturer for the simple reason that his facility does not possess the necessary sophisticated equipment for this measurement. This fact argues for an independent testing organization with a reputation for credibility that can be designated by the government for the performance of this type of testing.

A new requirement aimed at controlling the spectral response characteristics of the solar cell is now being included in some specifications. This requirement is in a sense tied to the radiation characteristics of the cell since the response of the cell in the short wavelength region of the solar spectrum is basically unaffected by space radiation while the long wavelength response is extremely sensitive to the effects of penetrating radiation.

The next class of operational requirements concerns itself with the cell's ability to retain its characteristics after interconnecting and storage. The controlling cell element is the contact. There are two basic tests required for cell contacts, a tape peel test made on the evaporated contact, and a pull test made on the contact when it has been soldered or welded.

All cells are tape tested, however some users only require that a fixed percentage of back contacts be tested, with the provision that any failure within the particular evaporation lot will result in all back contacts from that lot being tape tested. All front contacts are tape tested. Tape testing is basically a culling process, separating obviously inferior contacts from the rest. There is a difference in tape requirements, approximately fifty percent of the users require Scotch Brand #600 tape be used, while the remainder are satisfied with Scotch Brand #810 tape. The former corresponds to an adhesion strength in excess of 390 grams per cm while the latter's strength is ~335 grams per cm. It has never been demonstrated that contacts passing #810 will fail when tested with #600.

The pull strength requirements are common to all specifications regardless of the interconnection method. There is a wide variation among users on the details of this test. The number of cells sampled from each evaporation lot ranges from as low as one to as high as two and one-half percent. The angle at which the pull test is to be made ranges from zero (shear) to ninety degrees. The allowable pull strength at a given pull angle ranges from 400 to 600 gms (90° pull). In the case of welded cells the same variation in sampling, test conditions, and limits is observed. Pull angles range from zero to ninety degrees and pull strength requirements range from as low as 250 gms for a ninety degree pull to 5 kilograms for a zero degree pull.

Some specifications limit the amount of electrical degradation caused by the method of interconnecting. Others require that the cell be capable of being reworked after soldering without experiencing significant loss in electrical output. Those specifications addressing this area usually allow from one half to one percent degradation after soldering. In the rework situation, a total average degradation of 1.5 percent is allowed with the additional allowance of up to 2.5 percent loss on a single cell. For welded cells the average electrical degradation after welding is limited to 0.5 percent with any single cell allowed to degrade by up to one percent.

Storage requirements vary widely. Generally the specifications call out a number of storage conditions and periods of time after which the cells shall still be capable of meeting all their functional requirements. In many specifications there are redundant requirements. For example cells are required to survive storage at 95% relative humidity (RH) over a temperature range of -55 to +65°C for thirty days. In addition to this there is a separate temperature-humidity requirement of 30 days at > 99% RH which allows up to two percent degradation in output.

Even though storage conditions should reflect worst case conditions, it is difficult to imagine that solar cells or panels would be stored anywhere on earth such that temperature ranges of -55 to +65°C are experienced for any significant period.

The temperature-humidity requirements vary widely as well. The most extreme requirement is for thirty days at 65°C and >99% RH. The allowable degradation is an average of two percent with any single cell allowed to degrade up to three percent. The most benign requirement is a three day cycle during which the cell experiences a temperature range between 37 and 52°C under 95% RH. This test allows a 1.5 percent degradation in power after test.

An unusual storage requirement has been included in one particular cell user's specification. A sample of cells from each shipping lot is left for sixty days at the manufacturer's facility. After sixty days the cells are retested. The cells now must show no more than a two percent

reduction in output power to be considered acceptable. Such a requirement appears unnecessary in light of the standard storage requirements usually placed on solar cells.

One other element of the cell must meet quasi-storage requirements, and that is the antireflection coating. The standard tests usually involve adhesion (tape peel), durability (eraser test) and humidity resistance (boil or steam tests). Once more the requirements differ from user to user. Those users that concern themselves with this element generally require that the coating be subjected to either direct immersion in boiling water or direct exposure to steam for a fixed period. Following this, the cells are in one case examined visually for evidence of defects, in another tape peeled, and in still another rubbed with an eraser.

The next class of operational requirements deal with the anticipated conditions the cell will experience during the mission. These involve temperature, pressure, and temperature cycling. The main concern is that the cell be capable of performing without deleterious changes in either its integrity or output. Temperature and pressure are usually dealt with by requiring a thermal-vacuum test. There is some consensus here, the typical requirement being exposure to a temperature of  $\sim 140^{\circ}\text{C}$  in a vacuum better than  $10^{-5}$  torr for one week. In the case of the welded cell the temperature is higher,  $\sim 200^{\circ}\text{C}$  for the same conditions of time and pressure. The amount of degradation allowed ranges from none to one and one-half percent in electrical output.

Temperature cycle requirements are a direct function of the mission. Unfortunately it is very difficult to duplicate the space environment in a cost effective manner and therefore compromises are made (air instead of vacuum, etc.) that may subvert the purpose of the test. Unfortunately, adequate comparative data are lacking.

One of the purposes of this program is to develop specifications for various mission classes. One of the key differences in mission classes is the thermal environment that the cell will experience. Many cell users do not consider this factor separately, merely requiring worst case conditions regardless of mission class. Cycling can be characterized by 1) temperature extremes, 2) number of cycles, 3) rate of temperature change and 4) dwell time. The lowest temperature required is  $-196^{\circ}\text{C}$  (liquid nitrogen) with other values ranging up to  $-75^{\circ}\text{C}$ . The highest temperature for soldered cells is  $140^{\circ}\text{C}$ , for welded cells a temperature of  $260^{\circ}\text{C}$  is the most severe requirement. Other values range from 65 to  $130^{\circ}\text{C}$ . The number of cycles varies from a low of 5 to a high of 1500 for soldered cells. For welded contacts, 2000 cycles is the most extreme. The rate of temperature change varies from a minimum of 8 to a maximum of  $100^{\circ}\text{C}/\text{min}$ . Dwell times range from one minute to twelve hours. The amount of degradation in electrical output allowed after cycling ranges from none to as high as three percent.

The other major concern after thermal cycling is the integrity of the contact. All specifications examined require that after cycling the pull strengths meet the minimum requirement originally placed on the contacts.

It should be noted that in many cases there is some deterioration in contact pull strength after cycling. However, the typical pull strength is usually well above the minimum requirements established and even though its value may be reduced from thermal cycling, it is still capable of satisfying the original pull strength requirements.

#### C. Control Requirements

The last group of requirements fall into the category of controlling requirements. Almost all specifications require that the parts to be delivered shall have passed acceptance testing. There is also a consensus concerning "design and construction" which is a statement to the effect that cells shall be made to the details set out in both the specification and the drawing. This is an acknowledgement that it is not feasible to have each and every cell manufactured by the supplier examined for conformance to all specification requirements. It is included to protect the customer in case of unusable defective parts.

Most specifications ask for some form of documentation relating to processes, materials and procedures for cell manufacture. They usually reserve the right to approve this documentation and to approve any proposed changes once the cell is in fabrication. This required documentation can range from a brief flow chart showing the main processing steps and quality assurance check points to an elaborate presentation which lists all materials and their sources, every detail in manufacturing, testing and quality assurance as well as any peripheral documentation relating in any way to the manufacture of the cell.

There is often a requirement of "chemical and physical compatibility" which requires that only materials which will in no way interfere with subsequent assembly operations such as glassing and interconnecting can be employed. Another standard control requirement relates to cell uniformity or interchangeability. This requires that all parts delivered shall be made in the same way and shall be capable of being interchanged without any effect on their function. Once again this can be classified as a protective requirement for the cell user.

Still another control requirements is part identification. Those requesting identification will, as a minimum, desire the electrical grouping to be marked on the part in a specified location using a technique and material subject to customer approval. Other identifying requirements may include the shipping lot, or even more importantly, the evaporation lot to be marked on the cell.

Usually a specification will have a "workmanship" requirement. This is an extremely vague statement subject to broad interpretation. Of all the requirements discussed, this probably ranks as the most subjective. As is the case with most of the control type requirements, the workmanship



statement is probably included to protect the cell user from any unknown problems that had not been foreseen. However, in this case, unlike previous control requirements, there is no specific test to determine if the requirement is satisfactory.

The final control requirement that is sometimes quoted is "reliability." The desire for reliability is critical, but to the best of our knowledge no formal testing has ever been done to generate a sufficient body of data to allow a first principles evaluation of solar cell reliability to be done. Perhaps if solar cells are some day produced to a standardized specification such a program could be undertaken. At this point in time, however, there are no hard data concerning cell reliability, defined in the classic sense, and hence the inclusion of such requirements has no bearing on the cell's actual reliability.

Before addressing the Quality Assurance Provisions of these specifications it might be well to discuss the concept of a standardized cell specification in light of the requirements that have been collated. As has now been shown there are a number of descriptive, operational and control requirements that are common to all specifications. Many of the descriptive requirements vary considerably. The operational requirements have been shown to be basically standard even though the limits on these requirements vary. It is a fact that the method by which solar cells are produced does not change to accommodate the variation in requirements. Although one customer demands 600 gm pull strength while another is satisfied with 400 gms, the manner in which the cell is contacted does not change. Therefore it is quite possible to standardize operational requirements by simply defining the most stringent set of limitations on any given operational requirement. Since the specifications used for this collation have in most cases already been applied to large scale production runs it is already an accomplished fact that extreme operational requirements can be met in practice. What, if any, impact on cost is yet to be determined. In point of fact it shall be demonstrated in the discussion of "Quality Assurance Requirements" that this element of the specification can have a rather large impact on cost.

#### E. Quality Assurance Provisions

For every requirement of any given specification there should be a corresponding test identified to verify with some degree of confidence that the manufacturer is complying with the given requirement. This is the purpose of the "Quality Assurance Provisions" section of the specification. Generally requirements are verified either by actual testing of the parts to the various provisions of the specification requirements, or by allowing the manufacturer to certify that the parts delivered will meet the requirements as stated. In a legal sense this latter approach protects the user, but in practice it is recognition of the fact that when the user receives the product there is no cost effective test method of verifying the requirement.

The basic content of this specification section is to outline the responsibilities of the cell manufacturer for assuring the quality of the delivered part. It describes the various test plans that shall be implemented to assure, on a statistical basis, that the product meets the requirements of the specification. It defines the type and level of documentation necessary. It establishes the rights of the user to information relating to the manufacture of the cell.

Generally there are three types of testing required. The first is given many names such as pre-production tests, qualification tests or type approval tests. The purpose of this test plan is to qualify the materials, procedures and processes that are involved in producing the particular solar cell needed. In principle the manufacturer may not deliver any parts to the user until this qualification phase has been successfully completed. The qualification test is usually the most extensive investigation made into verifying cell requirements. As with the other two types of testing, there are various sampling plans employed. One sampling plan used is the lot tolerance percent defective (LTPD), imposing a tighter test level for qualification than for acceptance. Other sampling plans are based on MIL-STD-105D. Still others employ what appears to be arbitrary sample populations for cell qualification.

Since many of these tests are destructive in nature, the type of sampling plan used can have a significant impact on cell cost. Cells which are destroyed in testing add to the cost of those cells delivered. In addition to those cells destroyed, there is the labor cost involved in performing and evaluating the qualification tests. In the case of a standardized cell, this costly qualification process might not have the same impact since it might represent an extremely small portion of a cell production run, provided all cells were manufactured to the same specification.

Cells that are used for qualification are required to have successfully passed the various in-process tests noted in the user's specification. An in-process test is an examination of the product made during the actual fabrication sequence to demonstrate conformance to a particular specification requirement. The number of in-process tests are generally few in number, but they usually are related to critical elements of the cell. Many specifications call out base resistivity verification as an in-process test; almost all require tape peel testing of the cell's contacts as an in-process test. Another common test is contact pull strength, which is usually done on cell samples from every evaporation lot. Other tests of this nature include antireflection durability tests, junction removal from the cell edges, and high temperature baking of soldered cells. Although not usually mandated, all cells are examined for conformance to both the cell drawing and the mechanical requirements of the specification during fabrication. The sampling plans used for in-process tests range from one hundred percent testing in the case of resistivity and tape peel testing to as low as one percent in the case of contact pull strength.

The third group of tests required by the quality assurance section of most specifications is acceptance testing. In some specifications the acceptance test requirements are redundant and appear to add unnecessary cost to the finished product. Interpreted literally, some acceptance test requirements imply strongly that in-process testing and control of materials, processes and procedures have almost no meaning. For example cells from each evaporation lot undergo a destructive pull test. If one properly assumes that each evaporation lot is done identically with respect to materials, processes and procedures, then the sum of the samples taken from all lots will represent a hundred evaporation lots. The number of pull samples taken will number from one to five hundred cells. To require that an additional smaller sample from this total now be tested does not appear to change the level of confidence already achieved by performing in-process testing. Another factor that is often overlooked is that destructive in-process tests can usually be done on parts that would normally be out of specification for other reasons. Outside of the labor cost involved in performing the in-process testing there is no additional cost impact. In the case of acceptance testing, cells that can be shipped are now destroyed. The added cost is a function of the number of cells required for test and the number of times that acceptance testing is required.

#### E. Preparation for Delivery

This section of the specification involves a description of how the cells are to be packaged. Generally the type of shipping container, the manner in which the cells are to be placed in the container, and the type of preservative material to be included along with the cells, is precisely defined. The other important item covered in this section is part identification and grouping for shipment. The amount of information required varies with each specification, but it usually includes the specification or part number, the shipping lot number, the date or period of manufacture and the electrical groupings contained.

#### F. Notes

This section appears in some specifications and it can be very useful. Precise definitions of terms employed in the main body of the specification are given as well as details concerning any special test equipment necessary for performing tests.

#### IV. QUESTIONNAIRE PREPARATION AND SURVEY

A Letter Report detailing the results of the specification collation was presented to the Ad Hoc Team for Solar Cell Standardization for review. Spectrolab was then directed to prepare a detailed questionnaire referenced to MIL-C-83443A,, a cell specification that had been developed for the Air Force, which was to be used in an industry-wide survey. The purpose of this survey was to solicit opinions and recommendations concerning those critical elements that should be contained within a standardized solar cell specification. In addition the questions concentrated on attempting to discover the rationale determining each particular organization's requirements.

The format of the questionnaire consists of an explanation of its purpose, instructions and guidelines for its completion, a set of general questions addressing the concept of standardization and a set of specific questions addressing the referenced specification, MIL-C-83443 Revision A.

After approval of the questionnaire by the Ad Hoc Team, the survey package was assembled and mailed to those organizations chosen to participate. Four specific organizational groups were included in the survey. Sixteen companies representing panel or spacecraft builders comprised the first group. Ten government organizations representing both NASA and DOD made up the second group. Four companies who are either manufacturing or contemplating manufacturing silicon solar cells for space applications comprised the third group. Finally OCLI, the sole supplier of coverglass for the United States was contacted for any input that they might deem appropriate. These organizations are listed in Table 5.

Table 5. Survey List

Western Development Laboratories Div,  
Aeronutronic Ford Corp  
Palo Alto, CA 94303

Applied Physics Laboratory  
Laurel, MD 20910

Ball Brothers Research Corp.  
Boulder, CO 80301

The Boeing Company  
Seattle, WA 98124

S and J Industries  
Div. of Fairchild-Hiller  
Alexandria, VA 22304

COMSAT Laboratories  
Clarksburg, MD 20734

General Electric Company  
King of Prussia, PA 19406

Grumman Aerospace  
Bethpage, NY 11101

Hughes Aircraft Company  
Los Angeles, CA 90009

Lockheed Missiles and Space Co.  
Sunnyvale, CA 94088

Martin-Marietta Corp.  
Denver, CO 80201

Rockwell International  
Downey, CA 90241

RCA/Astro-Electronics Div.  
Princeton, NJ 08540

TRW Systems Group  
Redondo Beach, CA 90278

Electro-Optical Systems  
Pasadena, CA 91107

NASA Goddard Space Flight Center  
Greenbelt, MD 20771

NASA Lyndon B. Johnson Space Center  
Houston, TX 77058

Jet Propulsion Laboratory  
Pasadena, CA 91103

NASA Langley Research Center  
Hampton, VA 23365

NASA Lewis Research Center  
Cleveland, OH 44135

NASA George C. Marshall Space Flight Center  
Marshall Space Flight Center, AL 35812

Naval Research Laboratory  
Washington, DC 20375

SAMSO (DYAE)  
Los Angeles, CA 90009

Air Force Aero Propulsion Laboratory  
Wright-Patterson AFB, OH 45433

Aerospace Corporation  
Los Angeles, CA 90009

OCLI  
City of Industry, CA 91746

Solarex  
Rockville, MD 20850

Simulation Physics, Inc.  
Burlington, MA 01802

Spectrolab, Inc  
Sylmar, CA 91342

## V. ANALYSIS OF SURVEY

The survey of government and private organizations, soliciting their opinions on solar cell standardization was completed in three months. Twenty-two of the thirty-one organizations invited to participate replied. A breakdown of the organizations solicited and the number which participated is given in Table 6. The results of this survey were presented to the Ad Hoc Committee on Solar Cell Standardization at a meeting held March 31, 1976 at Goddard Space Flight Center.

### A. General Questions

The general questions, which only made up approximately five percent of the questionnaire, elicited the most significant response with respect to the attitude of the industry toward the concept of cell standardization. The consensus definition of standardization established a number of very important points. According to those organizations replying to the survey, standardization was defined in the following terms. "The establishment of acceptance criteria involving limited standardized variables in the use of materials, processes, dimensions, mechanical and electrical performance that offers cost reduction with improved reliability and delivery schedules. A cell that is mandated by the prime contractor." Thus it was apparent that the attractive features of standardization were cost reduction, improved confidence in the product and ease of procurement which is implied by the reference to improved delivery schedules.

However when asked what amount of cost reduction at the cell level would make standardization attractive, the replies were quite surprising. According to the federal organizations, no change in cost would still make the concept attractive because of the savings that would be accomplished at the system level in such activities as testing and qualification. As would be expected there was a spectrum of opinions ranging from a slight increase in cell cost to a greater than fifty percent reduction. The private sector tended to confirm the opinion expressed by the federal group, in this case an average reduction in cost of fifteen percent would be acceptable with the range extending from no reduction to two hundred percent. The rationale for this opinion agreed with the federal group, namely the cost impact would more likely be at the panel level since the cell does not represent the major cost element in most solar panels.

Since standardization could imply lack of change in space cell technology, the industry was queried for an opinion on what projected changes were anticipated within the next three years. Once again there was good agreement between the federal and private organizations. Both anticipated improvements in initial power, the implementation of welding technology, flight use of wraparound contact solar cells and some groups projected improvements in coverglass technology and a movement toward thinner cells. Most of these projected changes in cell technology might not be severely impacted by standardization, providing their definition of the term was correct.

Table 6  
Survey Response

<u>Organization</u>	<u>Solicited</u>	<u>Replied</u>
Private	16	13
Federal (NASA-DOD)	10	8
Solar Cell	4	1*
Filter	1	0

\*One additional reply was sent directly to the Ad Hoc Team for Solar Cell Standardization.



Another situation relating to standardization involved the various types of mission classes; planetary probe, geosynchronous, low orbit, that might require specific types of cells and therefore additional specifications. The survey yielded information that strongly implied that the differences in various mission classes could be satisfied with one or two types of cells. According to the industry, the various mission classes could be categorized by changes in three environmental parameters; 1) space radiation type, electron or proton, and fluence level, which could range from  $10^{13}$  to  $10^{16}$  equivalent 1 MeV electrons/cm<sup>2</sup>, 2) thermal cycling conditions involving operating temperatures and total number of cycles experienced, and 3) mission lifetime which could extend from a number of months to ten years.

When questioned about the concept of "stockpiling" standardized cells, the replies showed some concern about long term storage effects, inter-agency rivalries that might impact schedules and the removal of the normal close working relationship between the panel fabricator and the cell manufacturer. However the general consensus seemed to indicate that there were no major obstacles toward this "stockpiling" approach.

The most interesting set of replies were obtained from the question asking about what the industry considered to be the major obstacles to cell standardization. The first objection involved the variation in customer requirements that might be mandated to meet the needs of a particular mission. This concern is connected with the mission class requirements and obviously could be satisfied by one or two types of cells, so it was not considered to be a major obstacle. A second concern that was expressed relates to this same matter of mission class cells, namely that the standardized cell might be "overdesigned" and therefore more costly for certain missions. Again it should be pointed out that it was not the intention of this contract to develop one single specification to produce one unique cell for all missions.

Of more significance was the expressed concern that cell standardization would ultimately lead to the loss of competitive advantage since all cells would be the same and thus constrain the panel manufacturer. In this general vein the most significant objection involved the feeling that the present heavy capital investment in assembly tooling made by the major panel manufacturers would be jeopardized if the standardized solar cell did not conform to their particular assembly tooling.

The final set of suggested obstacles to cell standardization rested on the concern that this approach would cause technological stagnation in cell progress by inhibiting the development and acceptance of "better" cells. This fear was also expressed by other organizations which suggested that the "standardized" cell would ultimately become the "only" cell available.

#### B. Specific Questions

The second section of the questionnaire consisted of approximately 250 specific questions relating to the details of MIL-C-83443A "General Specification for Silicon Solar Cells," the reference specification for this effort. Questions concerning specification values, requirements and reasons for particular preferences were asked. The replies were collated and analyzed in order to develop a "hoped for" consensus specification.

There was some evidence of polarization with regard to the sampling methods used to control the "quality" of the cells. It was also apparent that in many cases variations in requirements (contact pull strength, AR voids, resistivity range, etc.) were the result of 1) cost considerations, and 2) internally generated data. There was general agreement that the critical factor affecting user confidence in solar cells was process control. Many organizations recommended that any standardized cell specification be made relatively simple. It was also felt by most that a method for assuring simulator control should be defined in the specification.

The first set of specific questions addressed the "Applicable Documents" section of the reference specification. There was general agreement that the pertinent sections of those documents deemed applicable should be clearly stated. However there was no clear agreement with respect to which documents should be referenced and there were a number of organizations which stated that this section of the specification served no useful purpose.

The referenced specification for simulator control, ASTM E-490 yielded some interesting observations. Less than half the organizations surveyed were familiar with the details of this document, yet there were no expressed objections to its inclusion in a standardized specification. Very few companies or agencies which expressed knowledge of this document had gone through a full scale verification of this specification with their in-house simulators.

When asked to describe the practical methods that were used to verify simulator accuracy and repeatability, most of those replying stated that balloon flown standard cells or "color" ratio tests were employed exclusively. In order to ascertain if the practical methods were useful those surveyed were asked if there had been any significant variation (greater than 2-3 percent) between their measurements of solar cells and those claimed by the suppliers. The response indicated that there have been no incidences of significant variation in the past three to five years.

A series of questions were asked that related to the control placed on the cell supplier with regard to those materials comprising the cell or assembly. Other than defining the materials; silicon, silver, etc., no requirements were directly imposed on the cell supplier to verify such properties as purity and grade. In general, no positive guidelines were given to the suppliers. However, control was strongly implied in the insistence of most users that material control should be an integral part of the process documentation that they had to approve.

The reference specification contained several other material properties requirements such as forbidding the use of radioactive or phosphorescent matter, requiring moisture and fungus resistance and referring to material compatibility. There was general agreement that these particular

requirements could be deleted on the grounds of practicality since many of these requirements were archaic or too vague to adequately define for control purposes.

Perhaps the most significant information was obtained from those questions pertaining to what was identified in the reference specification as a Process Identification Document (PID). All organizations use some variation of this type of document in their specification for solar cells. It is frequently referred to as a Manufacturing Control Document (MCD) or as a Change Control Document. In the final analysis, this document is used for formal control of the cell supplier's processes, materials, in-process testing and the like. It appeared that proper implementation of this document was perhaps the most single important item for the development of a standardized specification for space silicon solar cells or assemblies.

The topic of silicon bulk resistivity produced some consensus. With only one exception, all users specified either nominal two (one to three) or nominal ten (six to fifteen) ohm-cm material. The allowable resistivity tolerance ranges described were determined from economic considerations, an important point. The main impetus for these tolerances was an effort to maximize silicon crystal yield and thus reduce cell cost. This cost consideration appeared as the rationale for many of the operational and descriptive requirements now in existence for space silicon solar cells. Of interest, the only other requirement formally placed on the silicon was polarity, although other parameters such as oxygen content, dislocation density and the like, are very influential factors in cell performance. Once again, the justification for not including these requirements was cost.

The subject of dimensions and weight showed a range in dimensional tolerances from  $\pm 0.075$  to  $\pm 0.125$ mm in outside dimensions and a consensus of  $\pm 0.05$ mm in thickness. These tolerances were determined by four factors, 1) assembly tooling, 2) the supplier cost, 3) coverglass tolerances, and 4) panel packing factor. Most organizations felt that weight requirements coupled with outside dimensions were not sufficient to control the ultimate cell thickness, since the influence of radiation on cell performance is determined in part by silicon thickness. Thus silicon thickness is a necessary requirement. Another important dimensional tolerance that can have an impact on cost is the squareness of the cell. Here there was significant variation, squareness values between 0.33 to 1 degree being quoted.

Junction location was considered to be a critical parameter for control due to the susceptibility of silicon solar cells to damage from low energy protons. The general recommendation was for an edge etched, zero gap cell, thus allowing complete protection of the active cell area to be accomplished by the coverglass which would eliminate the costly conformal coating operation that is often necessary to completely protect the active area of the cell from low energy protons.

Although more advanced cells (violet type) have been designed with contact pads, the survey showed a general reluctance on the part of panel manufacturers to depart from the traditional ohmic bar interconnect which was as narrow as 0.50mm and as wide as 1.25mm. This variation in width was the result of differences in assembly tooling between panel makers. Grid

design was not considered to be critical provided the cell manufacturer could supply cells meeting the necessary power requirements.

The answers to the questions concerning antireflection coating requirements were quite revealing. Generally only two types of coatings are specified, silicon monoxide or tantalum pentoxide. No direct requirements are placed on the optical properties of these materials, but certain requirements addressing either allowable degradation or minimum appreciation when the cell is glassed imply that these materials possess a certain index of refraction. The physical property of most concern is coverage, while the most critical mechanical property is durability.

The limitations placed on coating defects such as voids were defended or rationalized by four basic arguments. The first was the concern for latent defects that might be currently manifested by the observable defects. The second was that defects occurring randomly were indications that proper process controls were not in operation. The third type of rationale was based on cosmetic objections which have historical precedence but are not presently important due to increased understanding of coating theory. The final argument was based on historical precedence and it was admitted that the values quoted were rather arbitrary and might not be valid.

Questions on electrical performance requirements showed that many organizations were procuring advanced cell types and that the consensus of opinion forecasted an almost complete change from the traditional to the advanced cell type within two years. At this time there was no definite agreement on power requirements or limits for the newer cells, not unexpected since the manufacturing technology is still in a transitional stage. One notable difference observed in this series of replies was the temperature at which cells were tested. Test temperature requirements technically can allow measurements to be made from as low as 23° to as high as 30° C. Since cell output is a sensitive function of test temperature, such a wide variation in test temperature cannot avoid creating confusion in the capabilities of particular cells to deliver a given organization's power needs.

All customers procure cells to both a lot minimum average and a minimum or lowest power grouping cell. The minimum cell requirement can have a significant impact on cell cost, since a relatively high minimum cell requirement will reduce cell yield. This point is understood by most organizations as indicated by answers to the question of what determines minimum cell output. There were two factors considered, 1) panel matching requirements, a technical consideration, and 2) cost, an economic consideration.

Questions relating to cell performance after glassing indicated that only approximately twenty percent of the cells delivered were unglassed and thus, to many groups, these questions had no meaning. The remaining organizations generally called out some type of sampling requirement to "verify" the cell's expected performance after glassing. However the techniques employed in "sample glassing" are not the same as those performed in actual glassing, which raises a question about the validity of such information. The results of this section of the survey tended to support the view

that the standardized specification should be written for a space silicon solar cell assembly (glassed cell) rather than for a cell alone.

In the area of "cell imperfections" there was general agreement on edge and corner chip allowances, although there was some concern expressed over the fact that there were no limits on quantity. Many of those surveyed did not consider chips and nicks as separate imperfections. The topic of gridline discontinuities indicated more of a concern for the location of the discontinuity (near the ohmic was a problem) rather than for the quantity. There was general agreement that the limits should be in terms of a total length which would be related to the total length of all the gridlines. Many felt that this type of imperfection was indicative of poor "workmanship" rather than an electrical problem. This relates again to the rationale for AR void limits, since it indicates process control or lack of same.

The contact void allowances of the reference specifications elicited a wide range of response. Many were only concerned about the area of the contact to which the interconnect would be attached. In these "critical" areas there would be no allowance for contact voids. Another sector of the industry would allow from zero (unrealistic) up to ten percent of the total contact area to be void of material. Once more the rationale for contact void requirements was either the "latent defect theory" or a method for assuring process control. In general there was agreement that the allowances called out in the reference specification were acceptable.

Requirements for soldering showed that the two percent silver content solder was used by almost all groups. However there was a wide variation in solder height requirements (a maximum allowable of .02mm to .15mm, a minimum allowable of .0025mm to .0175mm). This was determined mainly by interconnect techniques and available assembly tooling. There was little agreement on an acceptable method for verifying this requirement. Some suggested methods were direct measurement using a profilometer or micrometer (costly) to indirect measurements such as solder weight. Although most groups were amenable to the reference specification allowance for solder coverage, others wanted the allowances made more stringent. As in the case of contact voids, there was a significant number of organizations that favored the critical area concept.

The allowances, and methods for assuring solder contact integrity showed great divergence from organization to organization. The de-wetting limits called out in the reference specification were acceptable to most groups. However, the majority stated that solder pull tests were performed at 90°, rather than the 45° pull angle described in this particular document. Minimum pull strength values varied from 250 to 600 gms, with a center point at 500 gms. The values used were based on: 1) experience, 2) supplier information and 3) cost. The amount of electrical degradation in cell performance after soldering was generally limited to one percent at power, however some organizations opted for zero degradation, which is unrealistic.

When queried on the workmanship standards those replying stated that they generally applied it in their specification, but no precise definitions of workmanship could be offered. Most groups allowed their quality assurance personnel to determine the limits of workmanship. The replies to this series of questions once more demonstrated the subjective nature of this particular requirement.

The next set of questions dealt with a relatively new form of interconnect technology, welding. Initial procurements have started, and most respondents expect significant numbers of weldable cells to be purchased within the next two years. It was therefore quite surprising to find many organizations professing little knowledge about welding technology. When questioned on the reference values required for weldable cell metallization thickness and surface finish many replied that these values were not ideal. There appeared to be a lack of reliable data to establish a high confidence that these values would be satisfactory to all those considering welding. Most agreed that the cost of a welded cell would be higher because of process adjustments and the necessity of verifying the new requirements placed on weldable cells.

The environmental performance requirements of the baseline specification were the subject of the next series of specific questions. It was found that high temperature-high vacuum testing was not generally done at the cell level. Those who did require such testing were satisfied with the temperature, time and vacuum limits set forth in the reference specification.

The temperature-humidity test requirement of 95% relative humidity was agreeable to those surveyed, but there was a divergence in the temperature limits which ranged from 30 to 65°C. Most called for 30 days exposure, although some required as little time as four days. The degradation allowances thought to be acceptable ranged from none to two percent.

As previously mentioned, the thermal cycling requirements varied according to mission. Most organizations wanted from 300 to 1000 cycles with the average centering at about 500 cycles. Most organizations used -195°C as the lower limit while the upper limit went from 80 to 150°C. The desired rate of temperature change varied from 5 to 50°C/minute and dwell times of from 15 minutes to 2 hours were desired. Most groups allowed the testing to be done under ambient pressure conditions to avoid additional cost, even though the influence of the environment might produce additional problems in data analysis. The degradation allowance of 1.5 percent was generally acceptable to those replying to the questionnaire.

Radiation requirements are usually included in cell specifications. Based on the survey it appears that many organizations depend on their own internally generated data for determining this requirement. Most of this data has been recently (1974 or later) generated. Those who do not possess internal data depend on the open literature for their information. The manufacturer rarely is asked to verify this requirement since it has usually been done by the procuring organization before the specification has been released.

Another requirement that fits into this category is radiometric properties. The cell vendors do not have the capability of determining this property and it is generally verified by the user. Thus the specification requirement is usually written to conform to the data already generated by the user or his testing agency.

Questions pertaining to the quality assurance section of the reference specification showed some significant differences in not only what requirements were verified, but the manner in which they were verified. Basically the quality tests fell into three categories; qualification testing, in-process testing and acceptance testing.

The definition of a qualification and fabrication lot were acceptable, but the sampling method of the baseline specification was not generally used. This plan is called the Lot Tolerance Percent Defective (LTPD) method and it is usually employed when very large sample populations are available. Most of those replying to this set of questions professed unfamiliarity with this type of sampling plan and opted for another sampling method designated the Acceptable Quality Level (AQL) plan. Regardless of which sampling plan was used, all organizations professed to be satisfied with their particular method because: 1) to them it was cost effective, 2) it was well understood and 3) it allowed correlation to past procurements.

The cell manufacturer placed a great deal of importance on in-process as opposed to acceptance testing. It was claimed that in-process testing allowed an early warning of any potential out of control situation which would allow the vendor to take appropriate action before the problem became critical. If instead, the vendor was forced to rely on acceptance testing, then in the event of a problem the realization would be too late to prevent a serious delay in cell delivery.

Allowing the vendor to provide a certificate of conformance in lieu of verification testing for some requirements of the specification was a practice followed by all. Most justified this philosophy on the grounds that it was a method of avoiding inequalities in the specification. Many organizations were prone to expand the vendor certification idea to other cell specification requirements.

There were a number of general comments and recommendations concerning the reference specification. Many felt it was too complex and confusing and recommended simplifying its format. There was a general feeling that cell "reliability" could be guaranteed by process control, and that the key to this was the vendor's Manufacturing Control Document. Some suggested that certain test requirements could be deleted, but there was no consensus on the particular requirements to be eliminated. It was suggested that temperature data on cell performance would be very helpful. There was a fairly strong feeling that some method for assuring simulator control on a daily basis should be defined in any standardized cell specification.

## VI. STANDARDIZED ASSEMBLY SPECIFICATION - FIRST ITERATION

Using the results of the survey and the reference specification as guidelines, a preliminary specification was prepared that would be more likely to conform to the needs of the majority of the industry.

Since one of the goals of this contract was to provide specifications that were applicable to various mission classes such as low orbit, synchronous and planetary, those cell performance parameters important to each mission class were identified. The first important distinction was the type and level of radiation that would be experienced. Depending on the particular orbit and operating lifetime, the cells could experience electrons, protons or some combination of the two. Fluence levels in terms of equivalent 1 MeV electrons could range from  $10^{13}$  to  $10^{16}$  electrons/cm<sup>2</sup>. Another critical difference in mission class involves the thermal environment. This has a direct influence on the thermal cycling requirements placed on the cell. Both the number of cycles and the extremes of temperature are determined by the particular mission class. The degree of confidence thought necessary for any given space solar cell is also influenced by mission duration which can range from a few months to ten years.

The preliminary specification consisted of two documents, the main document addressing the cell requirements, applicable documents, quality assurance provisions and packaging requirements. The second document was the specification sheet which described the materials to be used in producing the assembly (cell and coverglass), the electrical, thermal cycling and radiation requirements, as well as a complete assembly drawing of the finished product. Three specification sheets were made up as examples of what could be included in such a document. The cells chosen represented both conventional and advanced types. The thermal cycling and radiation requirements used illustrated how such a document could deal with various mission classes.

The preliminary specification eliminated all references to such terms as workmanship and reliability. The former was eliminated since the interpretation could be extremely subjective, while the latter was eliminated on the grounds that no firm data base existed to allow a formal reliability analysis to be performed for space silicon solar cells. With regard to quality requirements, this specification attempted to combine the electrical and mechanical requirements for temperature-humidity tests to make the test conform to the realistic concerns of the user.

The assembly test temperature for electrical performance was fixed at 28°C to avoid the confusion that now exists due to various test temperatures called out by different organizations. This document was still relatively weak with regard to simulator control and an adequate definition of AMO test conditions.

The specification emphasized in-process testing since, as mentioned previously, this allows more control of the vendor's processes on a daily basis and thus can alert both the vendor and procurement agency to potential



problems that might impact delivery schedules. Since in-process testing implies relatively small sample populations, the AQL sampling test plan was incorporated for all quality assurance tests.

Another unique feature of this specification was the incorporation of an information requirement section. These requirements called for rudimentary spectral response information since this parameter is a controlling factor in the cell's behavior under radiation. The radiometric properties of the assembly were to be determined on a one time basis since these control the cell operating temperature, thus influencing cell output power. The radiation performance of the assembly was to be based on lot minimum average requirements, implying strongly that a distribution of cells be tested, rather than an "average" group. Finally the electrical performance for at least two additional temperatures was to be determined both before and after radiation to avoid the uncertainty in projecting cell performance during the life of the mission. This specification is included in this report as Appendix A.

The preliminary specification was carefully reviewed at a NASA sponsored Workshop on Cell Standardization held in Cleveland during August 1976. Representatives from both private and government organizations participated in this workshop. The preliminary specification was divided into smaller sections which provided the basis for the individual workshop sessions. An economic analysis of solar cell cost was provided by Pepperdine Research Institute. In brief, it was rather pessimistic concerning the possibility of significantly reducing the cost of the cell by any approach. This presentation is included in this report as Appendix B. At this point, the requirements of the contract were completed except for final reporting.

After receiving the inputs from the various working groups, the Ad Hoc Team for Solar Cell Standardization then modified the preliminary specification. This second draft was then presented to the space silicon solar cell manufacturers and panel makers for their comments. Following this, a third draft was submitted to the NASA Low Cost Systems Office Power Equipment Panel by the Ad Hoc Team for Solar Cell Standardization on April 14, 1977.

## VII. CONCLUSIONS

Based on the results of this study it does not appear that standardization of space silicon solar cells will bring about a significant reduction in their cost. There is some evidence that standardization might result in substantial cost savings at the subsystem level, but this has not definitely been proven. The main reason for this situation is the fact that the market for space silicon solar cells is relatively inelastic and there is no evidence that this condition will change in the near term future. This static market means that any cost reduction would not benefit the cell manufacturers since it would merely act to reduce their already limited profit margins. It is possible that a guaranteed market for cells that could be accurately forecasted would allow efficiency of operation and thus balance the potential erosion of profit margin. In this situation there is a possibility that some small cost savings could be achieved at the cell level.

Assuming that standardization is still an attractive proposition because of cost savings at the subsystem or system level, there are still some serious obstacles to a successful implementation of this concept. Many panel fabricators have large capital investments in assembly tooling that put certain constraints on the cell configuration. Unless the standardized cell could be made to conform to their tooling, they would be reluctant to jeopardize their capital investment by accepting a nonconforming cell design. In light of the rapid changes now occurring in both cell and cover technology, the industry does not appear to be receptive to any situation, such as standardization, that could impede further technological progress in improving space silicon solar cells.

Even if these objections can be overcome, standardization will not occur in the eyes of the cell manufacturers unless it is mandated by both NASA and DOD, since the latter organization presently is responsible for the majority of space silicon solar cell procurements. In the event that this does come to pass, the initial procurements of such components will be relatively costly. This additional cost will be the result of the necessary "learning experience" of the cell manufacturers and the concern of the procuring agencies that the cell they receive is one that inspires a high degree of user confidence. This concern will probably result in a specification that will be on the average more complex and more demanding than those now being employed.

## APPENDIX A

## SPECIFICATION SHEET A

### 1.0 SCOPE

1.1 This specification sheet covers all quantitative parameters referenced by the General Specification for Silicon Solar Cell Assemblies for Type C weldable silicon solar cell assemblies to be used for space flight.

### 2.0 REQUIREMENTS

#### 2.1 Materials (3.2)

2.1.1 Silicon: Boron doped, single crystal p-type with resistivity between 1 and 3 ohm-cm.

2.1.2 Contact materials: Evaporated titanium, overcoated with evaporated palladium, in turn overcoated with evaporated silver.

2.1.3 Antireflection coating: Tantalum pentoxide ( $\text{Ta}_2\text{O}_5$ )

2.1.4 Coverglass adhesive: Dow Corning 63-489.

2.1.5 Coverglass: Corning Glassworks 7940 fused silica.

#### 2.2 Thickness and Surface Finish (3.3.5.1)

2.2.1 Contact thickness: The thickness of the contact system required in 2.1.2 shall be no less than 6  $\mu\text{m}$  in the designated areas shown in Figure 1 (Note 2).

2.2.2 Surface Finish: The surface finish in the designated areas shown in Figure 1 (Note 2) shall be no greater than 250 nm RMS.

2.3 Electrical Output (3.4.1): Lot minimum average of 418 mA at 470 mV. Minimum assembly shall be 380 mA at 470 mV. Assemblies separated into 4 mA groupings at 470 mV starting at 380 mA. Average of each group is defined as group midpoint, e.g. 380-384 = 382 mA.

2.4 Temperature Cycling (3.4.3): Cycling shall be done in a vacuum of  $10^{-4}$  Torr or lower. Two hundred and fifty cycles between  $-50^\circ\text{C}$  and  $+200^\circ\text{C}$  at a maximum rate of  $25^\circ\text{C}$  per minute. Assemblies to dwell at  $-50^\circ$  and  $+200^\circ\text{C}$  for a minimum of 10 minutes.

2.5 Charged Particle Radiation Resistance (3.5.1.4): The average output of these assemblies when exposed to a normal incident particle fluence of  $1 \times 10^{15}$  1 MeV electrons/cm<sup>2</sup> shall be no less than 350 mA at 420 mV.

### 3.0 QUALIFICATION

3.1 Particle Irradiation (4.6.11): After the irradiation of 2.5, the assemblies shall be stored at room temperature ( $15-30^\circ\text{C}$ ) for at least 60 days before final electrical testing.

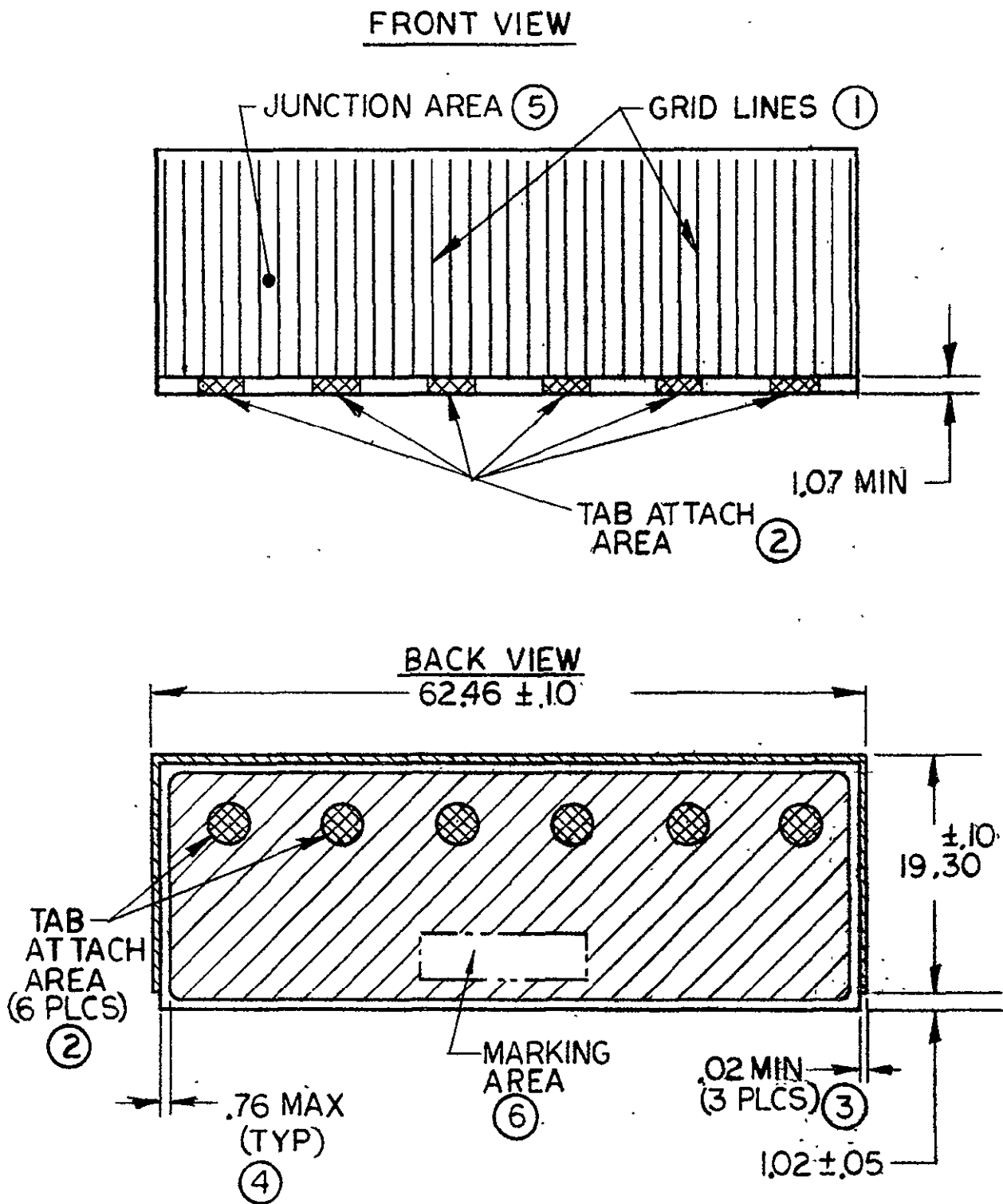


FIGURE 1  
 DIMENSIONS OF 2.0 CM X 6.2 CM SILICON SOLAR CELL  
 ASSEMBLY

NOTES FOR FIGURE 1

2.0 CM x 6.2 CM Silicon Solar Cell Assembly

1. All dimensions in millimeters.
2. Front contact bar shall be full length of cell.
3. Silicon cell thickness is  $.254 \pm .05$  mm.
4. The cell assembly shall be capable of seating flat in a cavity of 62.70 mm x 20.62 mm.
5. Coverglass thickness shall be  $.203 \pm .05$  mm.
6. Average assembly weight of a shipping lot shall not exceed 1745 milligrams.

Drawing Reference:

1. Number and width of gridlines optional (meet requirements of Para. 3.4.1).
2. Critical contact areas for tab attachment.
3. Coverglass shall cover the entire front surface except contact bar and shall extend over 3 cell edges.
4. Maximum bare silicon frame.
5. Junction area front surface only.
6. Marking as specified in Para. 3.3.2.

## SPECIFICATION SHEET B

### 1.0 SCOPE

1.1 This specification sheet cover all quantitative parameters referenced by the General Specification for Silicon Solar Cell Assemblies for Type B silicon solar cell assemblies to be used for space flight.

### 2.0 REQUIREMENTS

#### 2.1 Materials (3.2)

2.1.1 Silicon: Boron doped, single crystal p-type with resistivity between 6 and 14 ohm-cm.

2.1.2 Contact materials: Evaporated titanium, overcoated with evaporated palladium, in turn overcoated with evaporated silver.

2.1.3 Antireflection coating: Tantalum pentoxide ( $Ta_2O_5$ ).

2.1.4 Coverglass adhesive: Dow Corning 93-500.

2.1.5 Coverglass: Pilkington-Perkin-Elmer 5% ceria doped microsheet.

2.2 Electrical Output (3.4.1): Lot minimum average of 288 mA at 470 mV. Minimum assembly shall be 264 mA at 470 mV. Assemblies separated into 4 mA groupings at 470 mV starting at 264 mA. Average of each group is defined as group midpoint, e.g. 264-268 = 266 mA.

2.3 Temperature Cycling (3.4.3): Cycling shall be done in an ambient of nitrogen gas. Five hundred cycles between  $-140^{\circ}$  and  $+120^{\circ}$ C at maximum rate of  $30^{\circ}$ C per minute. Assemblies to dwell at  $-140^{\circ}$  and  $+120^{\circ}$ C for a minimum of 5 minutes.

2.4 Charged Particle Radiation Resistance (3.5.1.4): The average output of these assemblies when exposed to a normal incident particle fluence of  $1 \times 10^{14}$  1 MeV electrons/cm<sup>2</sup> shall be no less than 266 mA at 430 mV.

### 3.0 QUALIFICATION

3.1 Particulate Irradiation (4.6.11): After the irradiation of 2.4, the assemblies shall be stored at room temperature ( $15-30^{\circ}$ C) for at least 30 days before final electrical testing.

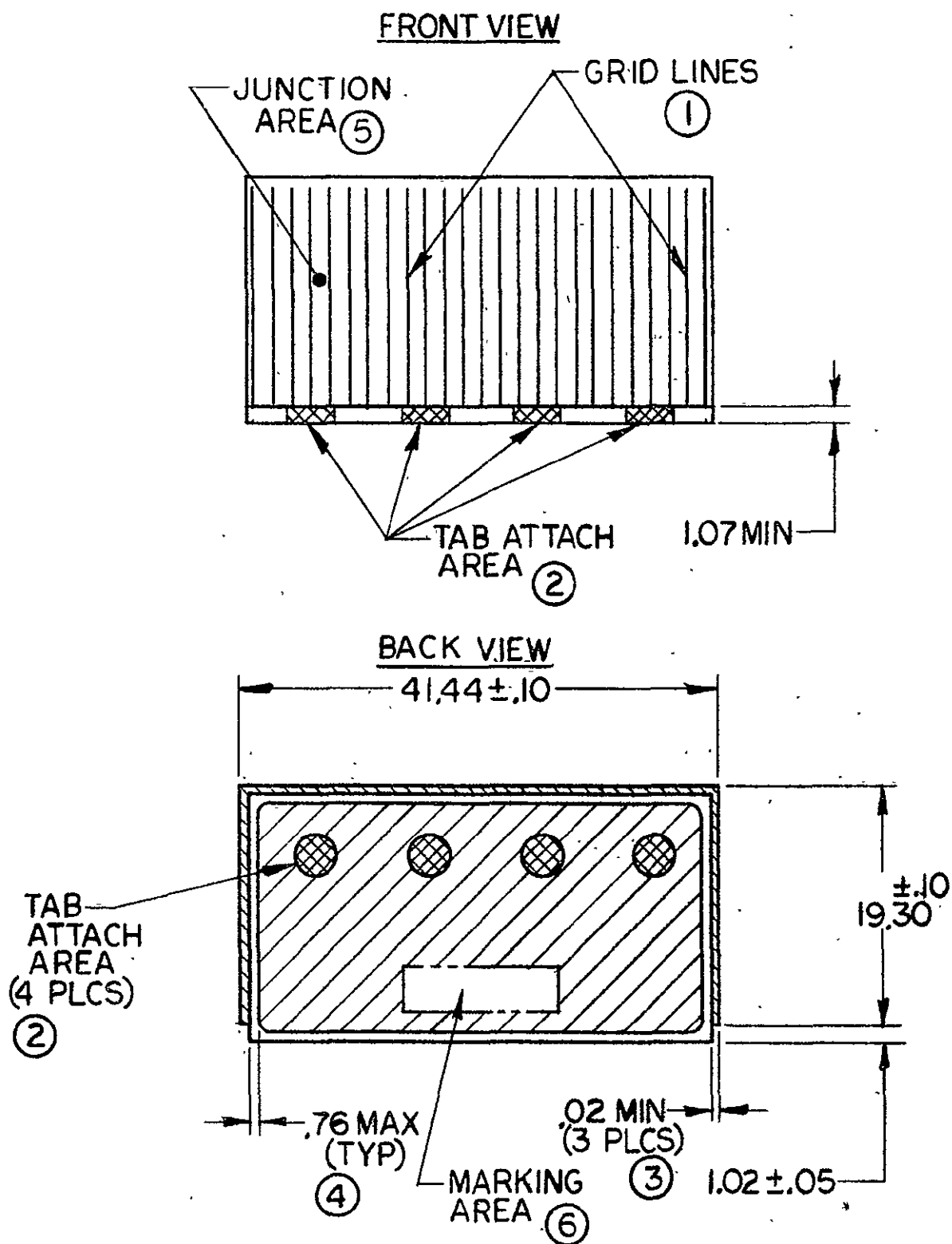


FIGURE 1

DIMENSIONS OF 2.0 CM x 4.1 CM SILICON SOLAR CELL ASSEMBLY



# NOTES FOR FIGURE 1

## 2.0 CM x 4.1 CM Silicon Solar Cell Assembly

- A. All dimensions in millimeters.
- B. Contact bar shall extend to edge of cell.
- C. Silicon cell thickness is  $.203 \pm .05$  mm. Contacts, adhesive and coverglass will add to this dimension.
- D. Front and back contact areas only will be solder coated per Para 3.3.5.3
- E. The cell assembly shall be capable of seating flat in a cavity of 41.70 mm x 20.62 mm.
- F. Coverglass thickness shall be  $.20 \pm .05$  mm.
- G. Average assembly weight of a shipping lot shall not exceed 1050 milligrams.

### Drawing Reference

- 1. Number and width of gridlines optional (meet requirements of Para. 3.4.1).
- 2. Critical contact areas for tab attachment.
- 3. Coverglass shall cover the entire front surface except contact bar and shall extend over 3 cell edges.
- 4. Maximum bare silicon frame.
- 5. Junction area front surface only.
- 6. Marking as specified in Para. 3.3.2.

## SPECIFICATION SHEET C

### 1.0 SCOPE

1.1 This specification sheet covers all quantitative parameters referenced by the General Specification for Silicon Solar Cell Assemblies for Type A silicon solar cell assemblies to be used for space flight.

### 2.0 REQUIREMENTS

#### 2.1 Materials (3.2)

2.1.1 Silicon: Boron doped, single crystal p-type with resistivity between 6 and 14 ohm-cm.

2.1.2 Contact materials: Evaporated titanium with evaporated overcoat of silver.

2.1.3 Antireflection coating: Silicon monoxide ( $\text{SiO}_x$ )

2.1.4 Coverglass adhesive: Dow Corning 63-489.

2.1.5 Coverglass: Corning Glassworks 7940 fused silica.

2.2 Electrical Output (3.4.1): Lot minimum average of 128 mA at 435 mV. Minimum assembly shall be 118 mA at 435 mV. Assemblies separated into 2 mA groupings at 435 mV starting at 118 mA. Average of each group is defined as group midpoint, e.g. 118-120 = 119 mA.

2.3 Temperature Cycling (3.4.3): Cycling shall be done in vacuum of  $10^{-4}$  Torr or lower. One hundred cycles between  $-100^{\circ}\text{C}$  and  $+100^{\circ}\text{C}$  at a maximum rate of  $25^{\circ}\text{C}$  per minute. Assemblies to dwell at  $-100^{\circ}\text{C}$  and  $+100^{\circ}\text{C}$  for a minimum of 15 minutes.

2.4 Charged Particle Radiation Resistance (3.5.1.4): The average output of these assemblies when exposed to a normal incident particle fluence of  $3 \times 10^{14}$  1 MeV electrons/cm<sup>2</sup> shall be no less than 108 mA at 415 mV.

### 3.0 QUALIFICATION

3.1 Particulate Irradiation (4.6.11): After the irradiation of 2.4, the assemblies shall be stored at room temperature ( $15-30^{\circ}\text{C}$ ) for at least 30 days before final electrical testing.

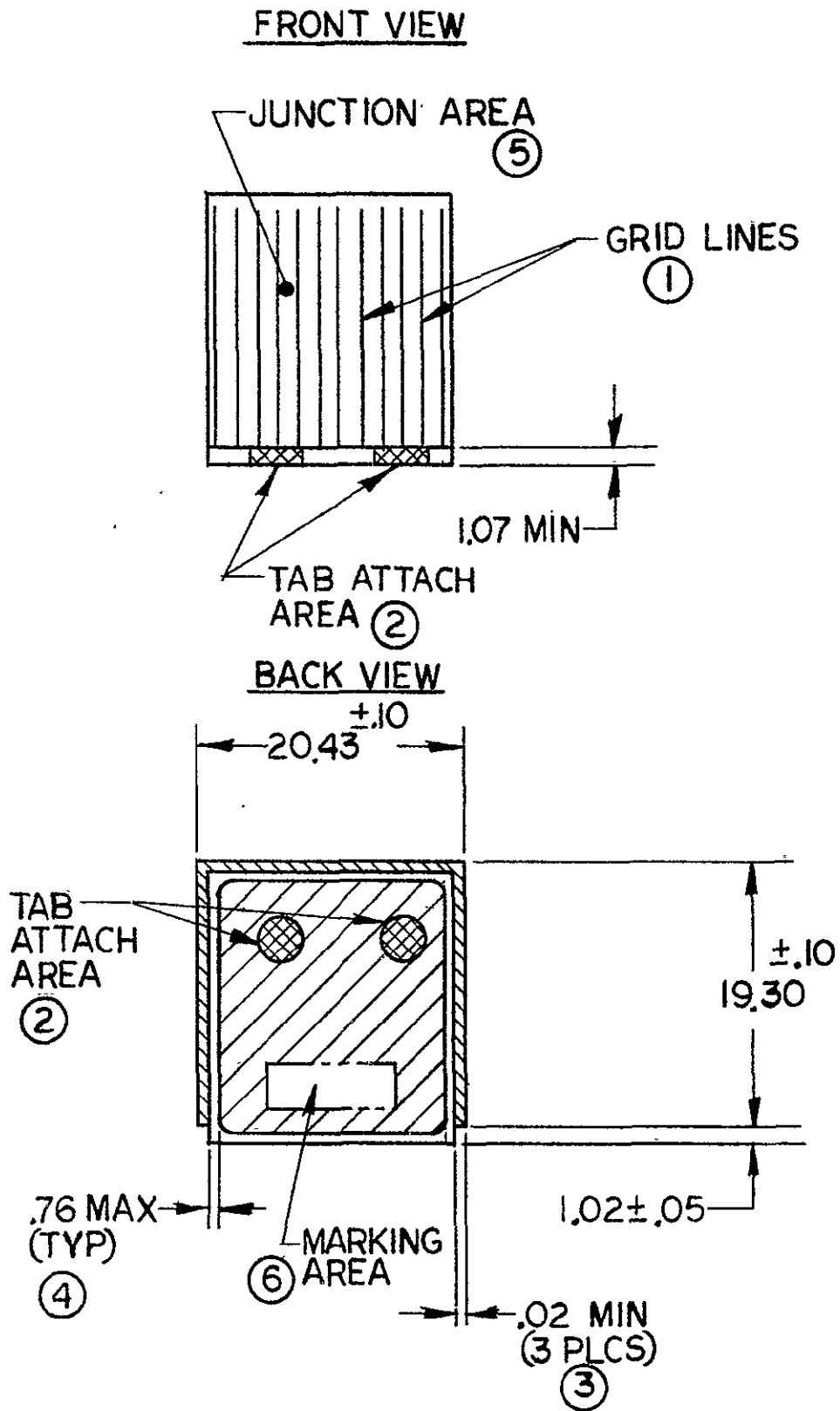


FIGURE 1  
DIMENSIONS OF 2.0 CM x 2.0 CM SILICON SOLAR CELL ASSEMBLY

NOTES FOR FIGURE 1

2.0 CM x 2.0 CM Silicon Solar Cell Assembly

- A. All dimensions in millimeters.
- B. Front contact bar shall be full length of cell.
- C. Silicon cell thickness is  $.305 \pm .05$  mm. Contacts, adhesive and coverglass will add to this dimension.
- D. Gridlines, front and back contact areas will be solder coated per Para. 3.3.5.3.
- E. The cell assembly shall be capable of seating flat in a cavity of 20.68 mm x 20.62 mm.
- F. Coverglass thickness shall be  $.23 \pm .05$  mm.
- G. Average assembly weight of a shipping lot shall not exceed 750 milligrams.

Drawing Reference:

- 1. Number and width of gridlines optional (meet requirements of Para 3.4.1).
- 2. Critical contact areas for tab attachment.
- 3. Coverglass shall cover the entire front surface except contact bar and shall extend over 3 cell edges.
- 4. Maximum bare silicon frame.
- 5. Junction area front surface only.
- 6. Marking as specified in Para. 3.3.2.

GENERAL SPECIFICATION  
FOR SILICON SOLAR CELL ASSEMBLIES

1.0 SCOPE

1.1 This specification covers the general requirements for space qualified silicon solar cells with transparent covers hereby defined as silicon solar cell assemblies.

1.2 Classification. Solar cells supplied to this specification shall be of the type detailed in the applicable specification sheet.

2.0 APPLICABLE DOCUMENTS

2.1 The following documents, of the issue in effect on date of invitation for bids or request for proposal, form a part of this specification to the extent specified herein.

SPECIFICATIONS

MIL-S-45743	Soldering, Manual Type, High Reliability Electrical Electronic Instrument Communication, and Radar for Aerospace and Control Systems, Procedures For
MIL-S-3464D	Desiccants, Activated, Bagged Packing Use and Static Dehumidification
MIL-F-22191	Barrier Materials, Transparent, Flexible, Heat Sealable
MIL-STD-105D	Sampling Procedures and Tables for Inspection by Attributes
MIL-C-45662A	Calibration System Requirements
NHB 5300.4(1C)	Inspection System Provisions for Aeronautical and Space System Materials, Parts, Components and services
MIL-STD-129F	Marking for Shipment and Storage
QQ-S-571E	Solder; Tin Alloy, Lead-Tin Alloy; and Lead Alloy
ASTM E-490	Specification for the Solar Constant and Air Mass Zero Spectral Irradiance

(Copies of specifications, standards, drawings, and publications required by suppliers in connection with specific procurement functions should be obtained from the procuring activity or as directed by the contracting officer).

### 3.0 REQUIREMENTS

3.1 Specification Sheets. The individual item requirements shall be as specified herein and in accordance with the applicable specification sheet.

3.2 Materials. All materials, as well as their pertinent properties, contained in the finished solar cell assembly, including but not limited to silicon, contact materials, antireflection coatings, coverglass, and coverglass bonding materials shall be as listed in the referenced specification sheet.

### 3.3 Design and Construction.

3.3.1 Uniformity of product. All solar cell assemblies shall be fabricated identically in procedure and material to the units which pass the qualification as specified in 4.3. No major changes in materials, fabrication techniques or procedures, assembly, inspection, or testing shall be made for subsequent units without notifying the procuring activity of the change and the effect of the change. In addition, the assemblies shall be manufactured and processed with an approved Manufacturing Control Document (MCD) which must comply with 4.3.4.1 of this specification. A major change is defined as one requiring a revision of the MCD.

3.3.2 Identification of product. Identification of individual solar cell assemblies shall consist of (1) manufacturing lot number as defined in 4.3.1.1, and (2) current output group according to 3.4.1. The marking shall be affixed to the rear of the solar cell assemblies in the area indicated on Figure 1. This identification shall be clearly readable after cleaning with water and alcohol and shall not degrade the specified mechanical, electrical, or environmental properties of the cell. Rubber stamping with an ink is acceptable.

3.3.3 Dimensions and weight. The solar cell assembly dimensions and the average weight of assemblies in each shipping lot shall be as listed in the referenced specification sheet.

3.3.4 Solar cell junction area. The solar cell junction area shall be located only on those regions of the cell identified in Figure 1 of the referenced specification sheet.

3.3.5 Contact configuration. Front and back surface contacts shall be sized and located in accordance with Figure 1 of the referenced specification sheet.

3.3.5.1 Thickness and finish. If applicable, the contact thickness and surface finish of the designated contact areas shall be as listed in the referenced specification sheet.

3.3.5.2 Contact appearance. There shall be no voids greater than 0.3 mm diameter penetrating the contact exposing either submetal or silicon. There shall be no evidence of contact peel or delamination when visually inspected with a microscope having 5 to 10 power magnification. A void is defined as the absence of the main component (silver or aluminum) of the deposited contact system. If the void is other than circular, it shall be no larger than .07 mm<sup>2</sup> in area.

3.3.5.3 Solderable contacts. If applicable, those portions of the cell contact area referenced in Figure 1 of the specification sheet shall be coated (tinned) with a solder alloy of approximately 62 percent tin, 36 percent lead, and 2 percent silver, per QQ-S-571E, or the latest revision. The solder coating shall be of uniform thickness not to exceed .08 mm above the surface of the cell. The solder coating shall cover a minimum of 95 percent of all contact area referenced and one hundred percent of any "critical" area referenced in this figure.

3.3.5.4 Contact cleanliness. There shall be no evidence of foreign matter; adhesive, oxide, etc., which would prevent metallic pull tabs from being attached to the cell contacts.

3.3.5.5 Contact function. Each contact area shall be capable of having metallic pull tabs attached to it in accordance with the applicable procedure of 4.6.12. If attached by soldering, the contact shall possess a pull strength of 800 gms. If attached by welding, the contact shall possess a pull strength of 350 gms. The method of testing is given in 4.6.13 of this specification.

3.3.6 Anti-reflective coating defects. The cell anti-reflective coating shall have no voids greater than 1.10 mm in diameter and no more than 5 voids per  $\text{cm}^2$  between 0.60 and 1.10 mm in diameter. If the defect is other than circular, there shall be no voids greater than  $1.0 \text{ mm}^2$  in area and no more than 5 voids per  $\text{cm}^2$  between 0.28 and  $1.0 \text{ mm}^2$  in area. A void is defined as the absence of antireflection coating from a required area.

3.3.6.1 Color and appearance. All cells shall conform to the color and appearance standards defined in the MCD.

3.3.7 Cell mechanical imperfections. These are defined to be chips, nicks and blisters. Chips are the absence of silicon which extend through the thickness of the cell. Nicks are the absence of silicon which do not extend through the thickness of the cell. A blister is the partial or complete separation of materials at their interfaces as evidenced by local delamination. The requirements of the following subparagraphs are to be met.

3.3.7.1 Blisters. There shall be no evidence of blisters on the cell contacts or anti-reflection coating.

3.3.7.2 Chips and nicks. The quantity and size of these defects shall not exceed the limits defined here as:

Edge chip or nick: 0.65 mm x 3.8 mm maximum, no limit on quantity.

Corner chip or nick: 1.5 mm hypotenuse maximum, no limit on quantity.

Interior nick: .05 mm x .05 mm or equivalent area, no limit on quantity.

Interior chip: None allowed.

3.3.8 Coverglass installation. The coverglass shall be installed, anti-reflection coating side up and overlapping the cell edges on 3 sides as shown in Figure 1 of the referenced specification sheet.

3.3.9 Coverglass imperfections. These are defined to be chips and scratches. A chip is the absence of material extending completely through the glass. A scratch is defined as the absence of material that does not extend completely through the glass. The cover shall have no imperfections exceeding those in the following subparagraph.

3.3.9.1 Corner chips: 1.25 mm hypotenuse maximum, no limit on quantity.  
Edge chips: 0.50 mm in from the edge maximum by 3 mm in length for a single chip. Total cumulative edge chip area allowed shall be 6 mm<sup>2</sup>.

Interior chips: None allowed.

Scratches: None wider than .08 mm, no limit on quantity.

3.3.10 Adhesive imperfections: These are defined as voids and foreign material. Voids are defined as the absence of adhesive. An interior void is defined as a bubble. Foreign material is any matter such as dust, lint, etc. which is contained within the adhesive. The adhesive bonding the cover to the cell shall have no imperfections exceeding those in the following subparagraph.

3.3.10.1 Edge voids: 1.0 mm in from any edge by 5 mm in length, no limit on quantity.

Bubbles: None greater than 1.25 mm in the biggest dimension, bubbles less than 0.15 mm in biggest dimension to be discounted. Bubble density no greater than 2 per cm<sup>2</sup>.

Foreign material: Total cumulative amount of foreign material not to exceed 5 mm<sup>2</sup>.

### 3.4 Performance.

3.4.1 Electrical output. Each solar cell assembly when measured at 28°C ± 2 shall be capable of providing the minimum electrical power required by the applicable specification sheet. Each solar cell shall be grouped according to the electrical output characteristics called out in the applicable specification sheet and shall have an electrical output not less than the minimum specified for the output group into which it is placed. The minimum average electrical output of any shipping lot will be as required by the applicable specification sheet. It shall be based upon the quantity of cells in each electrical group. Actual measured output of individual cells shall not be used.

3.4.2 Storage temperature and humidity. Each solar cell assembly shall be capable of meeting the requirements of the following subparagraphs after storage for a continuous period of 30 days at a minimum temperature of 45°C and a relative humidity of at least 90 percent.

3.4.2.1 Electrical output after temperature and humidity. The permissible current output degradation at the cell voltage as specified in the applicable specification sheet shall not exceed 1.5 percent for any cell based on actual values measured before and after the exposure and after corrections are made for variation in measurement conditions by a method mutually agreed to by the procuring activity and the cell manufacturer.

3.4.2.2 Color and appearance after temperature and humidity. The requirements of 3.3.6.1 shall be met after storage.

3.4.2.3 Mechanical imperfections after temperature and humidity. The requirements of 3.3.7.1 shall be met after storage.

3.4.2.4 Contact electrical integrity after temperature and humidity. Each assembly shall be capable of having four metallic pull tabs, two on the



front and two on the back contact area, attached to it in accordance with the applicable procedure of 4.6.12 without degrading the cell output more than 1.5 percent at the cell voltage specified in the referenced specification sheet. The average output current degradation for any sample of cells shall not exceed 1.0 percent. The calculated degradation shall use the final current output obtained from 3.4.2.1 as the initial current output for this test. These results shall be based on actual values measured before and after the exposure and after corrections are made for variation in measurement conditions by a method mutually agreed to by the procuring activity and the cell manufacturer.

3.4.2.5 Contact pull strength after temperature and humidity. Each tab shall possess a pull strength of 600 gms if soldered or 250 gms if welded after being subjected to the conditions specified in 3.4.2.

3.4.3 Contact attachment and temperature cycling. The solar cell assembly shall be capable of meeting all requirements specified below after having had 4 contact pull tabs attached to it in accordance with the applicable procedure of 4.6.12, and then having been subjected to the conditions of temperature cycling given in the referenced specification sheet.

3.4.3.1 Electrical output after temperature cycling. After attaching the tabs and temperature cycling, each cell shall meet the electrical requirements specified in the applicable specification sheet, except the maximum allowed current degradation at the cell test voltage shall be 2.5 percent for any single cell, and 1.5 percent average for any sample of cells. The average degradation shall be based on electrical output measurements of all cells including rejected ones. Also, this degradation shall be based on actual values measured before and after the temperature cycling and after corrections have been made for variations in measurement conditions. The method for these corrections shall be mutually agreed upon by the procuring activity and the manufacturer.

3.4.3.2 Contact pull strength after temperature cycling. The contact pull tab attached to the cells prior to temperature cycling specified in 3.4.3 shall possess a 45° pull strength of 250 gm minimum for welded tabs and 600 gm for soldered tabs. A cell shall be considered to have failed this test if any one contact pull tab does not meet this requirement.

3.4.3.3 Color and appearance after temperature cycling. All requirements specified in 3.3.6.1 shall be met after temperature cycling.

3.4.3.4 Mechanical imperfections after temperature cycling. All requirements specified in 3.3.7 shall be met after temperature cycling.

3.4.4 Contact electrical integrity. Each cell or assembly shall be capable of having four metallic pull tabs, two on the front and two on the back contact area, attached to it in accordance with the applicable procedure of 4.6.12 without degrading the cell output more than 1.5 percent at the voltage specified in the referenced specification sheet. The average output current degradation for any sample of cells shall not exceed 1.0 percent. These results shall be based on actual values measured before and after the attachment and after corrections are made for variation in measurement conditions by a method mutually agreed to by the procuring activity and the cell manufacturer.

3.5 Information. The following performance characteristics shall be obtained for the solar cell assemblies produced to this specification. This information shall be obtained as part of the qualification phase.

3.5.1 Selection method. A sample of assemblies from the qualification lot shall be selected in a random manner, proportional to the electrical distribution of the qualification lot. This sample, defined as the information group, shall consist of at least twenty assemblies, and shall then be tested in the following sequence.

3.5.1.1 Spectral response. The red-blue ratio will be obtained using the method described in 4.6.14 of this specification. The red-blue ratio is defined as the short circuit current obtained with the appropriate cut-off filter placed over the cell (red) divided by the difference in short circuit currents measured with and without the cut-off filter (blue). These measurements shall be made using a solar simulator meeting the requirements of 4.6.7.3 of this specification. The value obtained in any subsequent test shall not be more than eight percent greater than the value obtained from the information group.

3.5.1.2 Radiometric properties. The radiometric properties of these solar cell assemblies shall be measured and recorded using the method of 4.6.8 of this specification.

3.5.1.3 Electrical-Temperature properties before radiation. Each solar cell assembly shall be measured at two temperatures other than that required in the applicable specification sheet. The method to be used is described in 4.6.7 of this specification. The two temperatures chosen shall be mutually agreed upon by the supplier and the procuring agency. The data shall be supplied with the qualification data.

3.5.1.4 Charged particle radiation resistance. Solar cell assemblies shall be chosen from the information group in a manner that the average power output of this sample is equivalent to the lot minimum average required in 3.4.1. These solar cell assemblies shall be measured using the method of 4.6.7 of this specification. They shall then be exposed to a normally incident particle fluence as specified in the referenced specification sheet using the method of 4.6.11 of this specification. The assemblies will then be measured under the same test conditions as prior to the radiation. The average output of the irradiated cells shall equal or exceed the output value listed in the applicable specification sheet.

3.5.1.5 Electrical-Temperature properties after radiation. Each solar cell assembly from the group tested in 3.5.1.4 shall be measured at the same two temperatures used for 3.5.1.3. This data shall be supplied with the qualification data.

#### 4.0 QUALITY ASSURANCE PROVISIONS

4.1 Responsibility for Inspection. Unless otherwise specified in the contract or purchase order, the supplier shall be responsible for the performance of all inspection requirements as specified herein. Except as otherwise specified in the contract or order, the supplier may use his own

or any other facilities suitable for the performance of the inspections specified herein, unless disapproved by the procuring agency. The procuring agency reserves the right to perform any of the inspections set forth in the specification where such inspections are deemed necessary to assure supplies and services conform to prescribed requirements.

4.2 Classification of Examinations and Tests. The inspection requirements specified herein are classified as follows:

- a. Qualification examinations and tests (see 4.3).
- b. Acceptance examinations and tests (see 4.5).
- c. In-process examinations and tests (see 4.4).

4.3 Qualification Tests. Qualification tests shall consist of the tests specified in Table I. All tests shall be conducted in the sequence indicated, and shall demonstrate compliance with the respective requirements shown in Table I. Unless otherwise specified all tests shall be conducted with coverglass installed as specified in the applicable specification sheet.

4.3.1 Qualification sampling for assemblies.

4.3.1.1 Selection of qualification lot. The qualification inspection lot shall be chosen from complete manufacturing lots that have successfully passed all the in-process examinations and tests described in 4.4. A manufacturing lot is defined as that group of assemblies wherein conditions of contact application are identical. Manufacturing lots shall be uniquely numbered. The qualification lot shall contain assemblies from each current output group specified in the applicable specification sheet in approximately the same proportion as required by the average output requirements also given in the applicable specification sheet.

4.3.1.2 Qualification lot size. The qualification inspection lot shall contain more than 500 solar cell assemblies.

4.3.1.3 Sample size. The number of assemblies to be examined and tested shall be chosen by the manufacturer according to the AQL method in conformance to General Inspection Level II of Table I and II-A of MIL-STD-105D. This shall apply to each of the groups of assemblies to be tested according to Table I of this specification.

4.3.2 Qualification sampling for cells.

4.3.2.1 Selection of qualification lot. The qualification inspection lot shall be chosen from complete manufacturing lots that have successfully passed all the in-process examinations and tests described in 4.4 prior to coverglass application. The average output of this qualification lot shall be adjusted in a mutually agreed upon manner between the manufacturer and the procuring agency to compensate for the change in electrical output that would occur if these cells were made into assemblies.

TABLE I  
QUALIFICATION TESTS

Item		Requirement	Test Method	Group A*		Group B		Group C	
				Welded	Soldered	Welded	Soldered	Welded	Soldered
1	3.3.2	Identification of product	4.6.3			8	8	8	8
2	3.3.3	Dimensions and weight	4.6.4.1, 4.6.5			6	6	6	6
3	3.3.5	Contact configuration	4.6.4.2	2	2	4	4	4	4
4	3.3.5.1	Thickness and finish	4.6.4.3	4					
5	3.3.5.2	Contact appearance	4.6.3.1, 4.6.6.1	3		5,13		5,13	
6	3.3.5.3	Solderable contacts	4.6.3.1, 4.6.5.1		3		5		5
7	3.3.5.4	Contact cleanliness	4.6.3.1	8	7	15	14	15	14
8	3.3.5.5	Contact function	4.6.12, 4.6.13	10	9	17	16	17	16
9	3.3.6	Antireflective coating defects	4.6.3.1, 4.6.6.2	5	4				
10	3.3.6.1	Color and appearance	4.6.3	7	6	3,12	3,12	3,12	3,12
11	3.3.7.1	Blisters	4.6.3.1	6	5	2,11	2,11	2,11	2,11
12	3.3.7.2	Chips and nicks	4.6.3.1	1	1	1	1	1,10	1,10
13	3.4.1	Electrical output	4.6.7.1			7	7	7	7
14	3.4.2	Storage temperature and humidity	4.6.10			9	9		
15	3.4.2.1	Electrical output after temperature and humidity	4.6.7.2			10	10		
16	3.4.2.4	Contact electrical integrity	4.6.12, 4.6.7.2			14	13		
17	3.4.3	Contact attachment and temperature cycling	4.6.12, 4.6.9					9	9
18	3.4.3.1	Electrical output after temperature cycling	4.6.7.2					14	13
19	3.4.4	Contact electrical integrity	4.6.7.2	9	8	16	15	16	15

\* Cells without cover glass

4.3.2.2 Qualification lot size. The qualification inspection lot shall contain more than 150 solar cells.

4.3.2.3 Sample size. The number of cells to be examined and tested shall be chosen by the manufacturer according to the AQL method in conformance to General Inspection Level II of Table I and II-A of MIL-STD-105D. This shall apply to each of the groups of cells to be tested according to Table I of this specification.

4.3.3 Selection of samples. Initial samples shall be selected at random from the qualification inspection lot. When the qualification inspection lot is composed of two or more sublots, such as current output groups, the number of samples from each subplot shall be approximately proportional to the corresponding subplot size. After a test has started, the manufacturer may add an additional quantity to the initial sample, but this may be done only once for any of the groups A through C and the added samples shall be subjected to all tests within the given group. The total samples (initial and added samples) shall determine the new acceptance number. The total defectives of the initial and second sample shall be additive and shall comply with an AQL inspection level of 1.5 percent. The manufacturer shall retain a sufficient number of cells from the qualification lot to provide for additional samples.

4.3.4 Qualification certification. The basis for qualification shall consist of the following:

4.3.4.1 Uniformity of product. The manufacturer shall submit a Manufacturing Control Document (MCD) describing all steps used in the manufacture and test of units to meet the requirements of this specification and the applicable specification sheet. To minimize cost, and optimize delivery and quality, these steps may utilize existing procedures that have been established as a result of inhouse programs. In this regard, variations in details and sequence that comply with the spirit and intent of the requirements noted herein may be proposed. Each MCD shall include, but not necessarily be limited to the following basic elements (any changes subsequent to MCD release shall be approved by the procuring activity):

- a. A detailed specification showing starting material parameters including, but not limited to purity, crystal orientation, doping material, history, conductivity type, and other data required to fully describe the cell the manufacturer intends to supply.
- b. A detailed flow chart showing all processing steps involved in the production of the device. Each step shall be identified by the title, number and sequence of its controlling document. A copy of the controlling Quality Assurance (QA) documents for each process step shall be provided. These QA documents shall be controlled by a document number and applicable revision letter.
- c. A copy of the vendor's in-house product flow document. This document delineates the detailed handling for the solar cell, including qualification, acceptance and in-process testing.
- d. A mechanical drawing of the solar cell with cover slip which complies with this specification and reflects the configuration the manufacturer intends to supply.
- e. Visual and color inspection criteria as desired by the cell manufacturer.

4.3.4.2 Certification of conformance. Compliance with the requirements listed below shall be certified. A copy of the test data, data reduction, and analysis upon which certification is based shall accompany the Certificate of Conformance. In the event that this certification is based upon data obtained from a source other than the manufacturer, this data shall be subject to approval by the procuring activity.

Materials (3.2)

Uniformity of Product (3.3.1)

4.3.4.3 Similarity. The following requirements may be verified by test or by a memorandum stating that the design has been proven by virtue of similarity to a previously qualified unit.

Solar cell junction area (3.3.4).

4.3.4.4 Destructive tests. Cells and assemblies submitted to destructive tests shall not be submitted as partial fulfillment of any order. Destructive tests are defined as those of 4.4.3.

4.3.4.5 Requalification. To maintain qualified status, cell assemblies shall be subjected to complete qualification tests, Table I, as follows:

- a. At time intervals not to exceed 13 months.
- b. Whenever significant physical characteristic or process change is introduced.

4.4 In-Process Sampling and Testing. The following requirements of the specification shall be verified during manufacturing using the appropriate sampling plan.

4.4.1 Sampling plan one - - - One hundred percent.

4.4.1.1 Silicon properties. Each full or partial ingot or block of silicon from which solar cells are to be manufactured shall be tested using the method of 4.6.2 to verify the resistivity, polarity and crystal perfection (single) of the silicon.

4.4.1.2 Other requirements. Table II lists those requirements that shall be verified by one hundred percent sampling as well as the method of verification. Those cells or assemblies not conforming to these requirements shall be rejected.

4.4.2 Sampling plan two - - - Non-destructive. The following requirements of the specification shall be verified during manufacturing using the test methods and sampling plan defined for the appropriate requirement.

4.4.2.1 Dimensions and weight. Prior to final electrical testing, the assemblies shall be formed into lots of 400 cells. Dimensions and weight shall be verified using General Inspection Level III of Table I of MIL-STD-105D to an AQL of 1.0 using the test methods of 4.6.4 and 4.6.5. In the event that the test lot fails, the assemblies shall be screened one hundred percent for dimensions and weight, rejecting all samples which do not meet the specification requirements.

TABLE II

## ONE HUNDRED PERCENT SAMPLING (IN-PROCESS TESTING)

<u>Item</u>		<u>Requirement</u>	<u>Test Method</u>
1	3.3.5.2	Contact Appearance	4.6.3.1, 4.6.6.1
2	3.3.6	Anti-reflective Coating Defects	4.6.3.1, 4.6.6.1
3	3.3.5	Contact Configuration	4.6.4.2
4	3.3.5.3	Solderable Contacts	4.6.3.1 and 4.6.5.1
5	3.3.5.4	Contact Cleanliness	4.6.3.1
6	3.3.6.1	Color and Appearance	4.6.3
7	3.3.7	Cell Mechanical Imperfections	4.6.3.1
8	3.3.8	Coverglass Installation	4.6.3.1
9	3.3.9	Coverglass Imperfections	4.6.3.1
10	3.3.10	Adhesive Imperfections	4.6.3.1

4.4.2.2 Thickness and finish. Each manufacturing lot shall be tested for conformance to 3.3.5.1 employing the method of 4.6.4.3 using Special Inspection Level S-4 of Table I of MIL-STD-105D to an AQL of 1.5. If the lot fails, a new sample using G.I.L. II and an AQL of 1.0 will be performed. If the lot fails once more, it shall be rejected or one hundred percent tested for rejects.

4.4.2.3 Electrical output. After electrically testing 250 assemblies, this defined test lot shall be sampled for electrical grouping using special inspection level S-4 of MIL-STD-105D to an AQL of 1.5. If the lot fails, a new sample using G.I.L. II of MIL-STD-105D shall be tested to an AQL of 1.0. If the lot fails again, the entire lot shall be retested.

4.4.3 Sampling plan three - - - Destructive. The following requirements of the specification shall be verified during manufacturing using the test methods and sampling plan defined for the appropriate requirement. A cell which is out of specification by virtue of a mechanical defect, unrelated to contact or antireflection coating adherence may be used to perform these tests.

4.4.3.1 Contact function. Before coverglassing each manufacturing lot shall be tested for conformance to 3.3.5.5 employing the method of 4.6.13 using special inspection level S-2 of Table I of MIL-STD-105D to an AQL of 4.0. If the lot fails, a new sample using G.I.L. I of MIL-STD-105D to an AQL of 1.0 shall be tested. If the lot fails again, the manufacturing lot shall be scrapped.

4.4.3.2 Contact electrical integrity. Before coverglassing each manufacturing lot shall be tested for conformance to 3.4.4 employing the method of 4.6.7.2 using special inspection level S-2 of Table I of MIL-STD-105D to an AQL of 4.0. If the lot fails, a new sample using G.I.L. I of MIL-STD-105D to an AQL of 1.0 shall be tested. If the lot fails again, the manufacturing lot shall be scrapped.

4.4.3.3 Anti-reflective coating defects. With the concurrence of the procuring agency, the same cells employed for 4.4.3.1 and 4.4.3.2 shall be tested for conformance to 3.3.6 using the method of 4.6.3.1 and 4.6.6.2. The test plan of 4.4.3.1 and 4.4.3.2 shall be employed.

4.5 Acceptance Testing. The following requirements of the specification shall be verified after formation of a shipping lot. A shipping lot is defined as a group of complete manufacturing lots made in conformance to the MCD which have successfully completed all in-process testing and which have an average electrical output equal to or greater than the requirements of 3.4.1.

4.5.1 Acceptance test sampling plan: The following requirements of the specification contained in Table III of this document shall be verified using the test method and sequence defined in this table. Acceptance shall be to an AQL of 2.5.

4.5.1.1 Sample size. Assemblies shall be selected randomly from the shipping proportionate to the electrical distribution of the lot in conformance to Inspection Level I of MIL-STD-105D.

4.5.2 Replacements. In the event sample assemblies are accidentally damaged prior to completion of specified test sequence, each such damaged



TABLE III  
ACCEPTANCE TESTS

<u>Item</u>		<u>Requirement</u>	<u>Test Method</u>	<u>Sequence</u>
1	3.3.2	Identification of product	4.6.3	13
2	3.3.3	Dimensions and weight	4.6.4.1 and 4.6.5	11
3	3.3.5	Contact configuration	4.6.4.2	10
4	3.3.5.2	Contact appearance	4.6.3.1	9
5	3.3.5.3	Solderable contacts	4.6.3.1, 4.6.5.1	8
6	3.3.5.4	Contact cleanliness	4.6.3.1	7
7	3.3.5.5	Contact function	4.6.12, 4.6.13	16
8	3.3.6	Anti-reflective coating defects	4.6.3.1	6
9	3.3.6.1	Color and appearance	4.6.3	5
10	3.3.7	Cell mechanical imperfections	4.6.3.1	4
11	3.3.8	Coverglass installation	4.6.3.1	1
12	3.3.9	Coverglass imperfections	4.6.3.1	2
13	3.3.10	Adhesive imperfections	4.6.3.1	3
14	3.4.1	Electrical output	4.6.7.1	12
15	3.4.4	Contact electrical integrity	4.6.12, 4.6.7.2	15
16	3.5.1.1	Spectral Response	4.6.14	14

assembly may be replaced by a new solar cell chosen at random from the lot under test. Each new assembly shall be subjected to all the tests in the test sequence. Accidentally damaged assemblies which have been replaced by new units shall not be included in determining acceptability of the lot under test.

#### 4.5.3 Rejection and resubmittal.

4.5.3.1 Rejection. Any assembly which does not meet any one or more requirements of any individual test specified shall be rejected.

4.5.3.2 Rejection and retest. When a shipping lot fails to meet the specified AQL, all items in the lot shall be rejected. The procuring activity shall be immediately notified of any rejected lot.

4.5.3.3 Disposition of rejected lot. The disposition of rejected shipping lots shall be in accordance with 4.5.3.4 and 4.5.3.5.

4.5.3.4 Resubmitted manufacturing lots. Manufacturing lots from which defectives have been screened or reworked and which are submitted for acceptance inspection, shall contain only devices which were in the original lot. Resubmitted lots shall be inspected for all characteristics; using tightened inspection only for the failed characteristics. No lot shall be resubmitted for acceptance inspection after a second rejection for the same defect. At the discretion of the procuring activity, testing of characteristics which are not affected by the screen process may be omitted for resubmitted lots.

4.5.3.5 Records of rejected lots. Adequate records of all rejected lots shall be maintained including lot number, quantity of cells, test data, type of test, reason for rejection and disposition, as a minimum. Two copies of each lot rejection record shall be sent to the procuring activity when disposition is made.

4.5.3.6 Disposal of samples. Solar cells subjected to destructive in-process tests and to acceptance testing shall be submitted to the procuring activity for disposition. These cells shall not be shipped on the contract or purchase order.

4.5.3.7 Defects in items already accepted. The investigation of a test failure could indicate that defects may exist in items already accepted. If so, the manufacturer shall fully advise the procuring activity of all defects likely to be found and methods for correcting them.

4.5.4 Quality conformance certification. A certificate of compliance shall accompany each shipment. The certificate shall provide evidence that all the acceptance and in-process provisions have been met.

#### 4.6. Test Methods.

4.6.1 Test methods and test conditions. The qualification, in-process and acceptance tests required in Tables I, II and III for solar cells or assemblies manufactured according to this specification shall be performed according to test methods and under test conditions stated below, unless otherwise specified in the applicable specification sheet.

4.6.2 Material characterization. The following material parameters shall be determined by methods chosen by the supplier and in common usage by the

industry on each full or partial ingot from which solar cells are to be manufactured.

- a. Dopant material, level and original form.
- b. Resistivity.

4.6.3 Visual inspection. Assemblies or solar cells shall be inspected with the unaided eye to verify the respective requirements.

4.6.3.1 Verification of visual inspection. The assemblies or solar cells shall be examined visually using a stereo microscope of 10X magnification or an optical comparator to verify the respective requirements.

#### 4.6.4 Dimensions

4.6.4.1 Overall dimensions. The overall dimensions of the assemblies shall be verified by seating them flat within a cavity of dimensions given in the specified figure. An optical comparator with overlay dimensions may be used to verify coverglass size and position.

4.6.4.2 Contact dimensions. The cell contact area dimensions shall be measured with an optical comparator, measuring microscope, or similar instrument.

4.6.4.3 Contact thickness and finish. Maximum contact thickness shall be measured perpendicular to and from the front surface of the cell with a microprofilometer or similar instrument.

4.6.5 Weight. The average assembly weight shall be determined by weighing samples of assemblies and dividing the group weight by the number of units in the group. The weighing accuracy shall be  $\pm 1.0$  percent.

4.6.5.1 Solderable contact thickness. The average thickness of the solder coating shall be obtained by measuring the weight increase of each manufacturing lot after soldering and dividing by the total number of units to derive an average solder weight. This weight, in conjunction with the required solder coated area and the density of the solder employed will be used to calculate the average solder thickness.

#### 4.6.6 Tape peel tests.

4.6.6.1 In-process: Plan one. Scotch Brand Magic Transparent Tape No. 810 or equivalent adhesive tape with an adhesion-to-steel value of at least 336 grams per cm width in accordance with FED-STD-147 shall be placed over the cell to completely cover the cell surface. The method of application shall be mutually agreed upon by the procuring agency and the cell manufacturer. The tape shall then be stripped from the cell at a 45 to 90 degree angle to the cell surface starting at the trailing edge of the gridline, peeling toward the ohmic contact edge of the cell. Following the peeling of the tape, the cell shall be inspected for conformance with Paragraphs 3.3.5.2 and 3.3.6.

4.6.6.2 In-process: Plan three. The solar cell without cover slip shall be placed in a beaker of boiling deionized water for 15 minutes. The solar cell shall then be removed and allowed to naturally cool to room temperature. Scotch Brand Magic Transparent Tape, No. 810 or equivalent adhesive tape with an adhesion-to-steel value of at least 336 grams per cm width in accordance with FED-STD-147 shall be placed over the cell to completely cover the cell surface. The tape shall be firmly rubbed

until the cloudy appearance of the tape disappears, assuring firm adherence of the tape to the cell. The tape shall then be stripped from the cell at a 45 to 90 degree angle to the cell surface starting at the trailing edge of the gridline, peeling toward the edge of the cell. Following the peeling of the tape, the contact area shall be inspected for conformance with Paragraph 3.3.6.

#### 4.6.7 Electrical output

4.6.7.1 Electrical current output test method. The electrical current output shall be measured with the light source of 4.6.7.3, at the constant voltage level, and light intensity specified in the applicable specification sheet. The assemblies shall be grouped into current output groups specified in the applicable specification sheet referenced in 3.4.1.

4.6.7.2 Electrical I-V curve output test method. The solar cell current-voltage characteristic shall be measured by illuminating the cell with the light source of 4.6.7.3, varying the load resistance across the cell, and plotting corresponding current-voltage data points. Short-circuit current is defined as current through a 1-ohm, or lower, load. Open-circuit voltage is defined as voltage at a current of 1 milliamper, or less.

a. Unless otherwise directed, the following measurement data may be used in lieu of 4.6.7.2.

a) <sup>B</sup> Current at fixed load voltage,  $I_L$ .

4.6.7.3 Light source. The light source to be used shall be artificial sunlight which approximates natural sunlight under air-mass-zero (AM0) conditions. It shall conform to the following requirements to be verified by the method described in each of the subparagraphs of this section.

4.6.7.3.1 Spectral distribution. The AMO solar spectrum shall be defined by the figure entitled Solar Spectral Irradiance, ASTM E-490, in the range from 300 to 1200 nanometers. The total energy in any wavelength band incident on the test plane shall not deviate from the same band of the figure referenced above by more than the following percentage:

<u>Wavelength Increment</u>	<u>± Percent</u>
20 nanometers	30
40 nanometers	25
60 nanometers	20
100 nanometers	10

The spectral content of the light shall be determined by at least one of the methods below:

- a. Direct measurement with a calibrated spectro-radiometer.
- b. Indirect (comparison) measurement with a number of sensors of different spectral response characteristics.

4.6.7.3.2 Intensity. The light intensity at the test plane (plane of front side of solar cell) shall be such that the average measured short circuit currents of the standard cells used for calibration is equal to the referenced short circuit current obtained from either a balloon flown standard cell or a cell supplied by the procuring activity. The deviation in short circuit current for any one standard cell used shall not exceed one percent of the referenced current value. The referenced value to be used shall be mutually agreed upon by both the procuring agency and the cell manufacturer.

4.6.7.3.3 Stability. The intensity shall be stable within  $\pm 1$  percent during any measurement period. If intensity-compensating measuring circuits are used, their speed of response shall be sufficiently fast to meet this stability requirement. Stability will be verified by measuring the short circuit current of a mutually agreed upon standard cell at least once every two hours. If the intensity has changed by more than  $\pm 1$  percent, the simulator shall be readjusted to yield the required short circuit current value. Assemblies measured during this period will be sampled to ascertain the effect of the lack of stability. In the event that the measured values of the sampled assemblies do not agree with those recorded previously, all assemblies tested during this period will be retested.

4.6.7.3.4 Uniformity. The intensity shall not vary by more than  $\pm 2$  percent across an area which is at least one centimeter greater in each dimension than the size of the assembly being tested. The intensity uniformity shall be verified through the use of a 1 cm x 1 cm or smaller silicon solar cell. This cell shall be placed in locations corresponding to the center and corners of the cell assemblies being tested. The  $I_{sc}$  values for the 1 cm x 1 cm at the five positions shall not vary by more than  $\pm 2$  percent from their average value.

4.6.7.4 Standard solar cells. All standard solar cells shall have spectral characteristics that are similar to those assemblies which are to be delivered under this specification. The spectral similarity between the standard cells and assemblies will be demonstrated by a method such as direct measurement of spectral response characteristics or the use of ratios derived by employing cut-on filters.

4.6.8 Radiometric properties. The radiometric properties of the front sides of the assemblies shall be measured as follows:

4.6.8.1 Solar absorptance. The spectral reflectance of electromagnetic energy shall be measured from 280 to 2500 nanometers with Edwards type integrating sphere equipment. The test data shall be integrated over the solar irradiance and the integral subtracted from unity to yield the solar absorptance.

4.6.8.2 Hemispherical emittance. The hemispherical emittance shall be measured by either one of the two methods below:

a. Measure spectral reflectance in the wave-length range from 2.0 to 26 micrometers and integrate over 300°K Planckian radiator function.

b. Measure power density required to maintain sample at an equilibrium temperature of 300°K in a liquid nitrogen-cooled vacuum chamber.

4.6.9 Temperature cycling. The assemblies shall be placed in a chamber at ambient temperature and pressure. The chamber temperature shall then be varied to alternately bring them to the upper and lower temperature limits

specified in 3.4.3. The dwell times at the temperature limits shall be not less than 2 minutes each. The time-rate of temperature change shall be within the limits specified in 3.4.3. The number of cycles is also specified in 3.4.3. The assembly temperatures shall be monitored during this test with suitable instrumentation.

4.6.10 Storage temperature and humidity. The assemblies shall be placed in a chamber at ambient pressure. The chamber temperature and humidity shall then be brought to the levels specified in 3.4.2 and maintained for 30 days.

4.6.11 Particulate irradiation. The assemblies shall be subjected to the spectrum and fluences of particle radiation as specified in the applicable specification sheet. The flux density shall be uniform over the area of the solar cell to within  $\pm 10$  percent. During the radiation, the assemblies shall be kept at approximately  $25^{\circ}\text{C}$ , but not exceeding  $40^{\circ}\text{C}$ . Immediately following irradiation, the test specimens shall be stored at the temperature and for the recovery time period specified in the applicable specification sheet. After this time period, they shall be tested at the temperature specified in the applicable specification sheet in accordance with 4.6.7.

4.6.12 Attachment of pull tabs. Four pull tabs, two on the front and two on the back contact area, shall be attached using the following applicable method.

4.6.12.1 Soldered. The pull tab shall be a pretinned flat copper ribbon of  $3.0 \pm 0.1$  mm width,  $125 \pm 25\mu\text{m}$  thickness and sufficient length for clamping in the pull tester as shown in Figure 2. MIL-S-45743 shall be used as a guide for soldering. The solder shall be the same as specified in 3.3.5.3.

4.6.12.2 Welded. The pull tab shall be a flat ribbon of silver plated molybdenum  $3.0 \pm 0.1$  mm width,  $75 \pm 25\mu\text{m}$  thickness and sufficient length for clamping in the pull tester as shown in Figure 2. The welding equipment and schedule shall be mutually agreed upon by the procuring activity and the cell manufacturer.

#### 4.6.13 Nonlimited 45 degree pull test

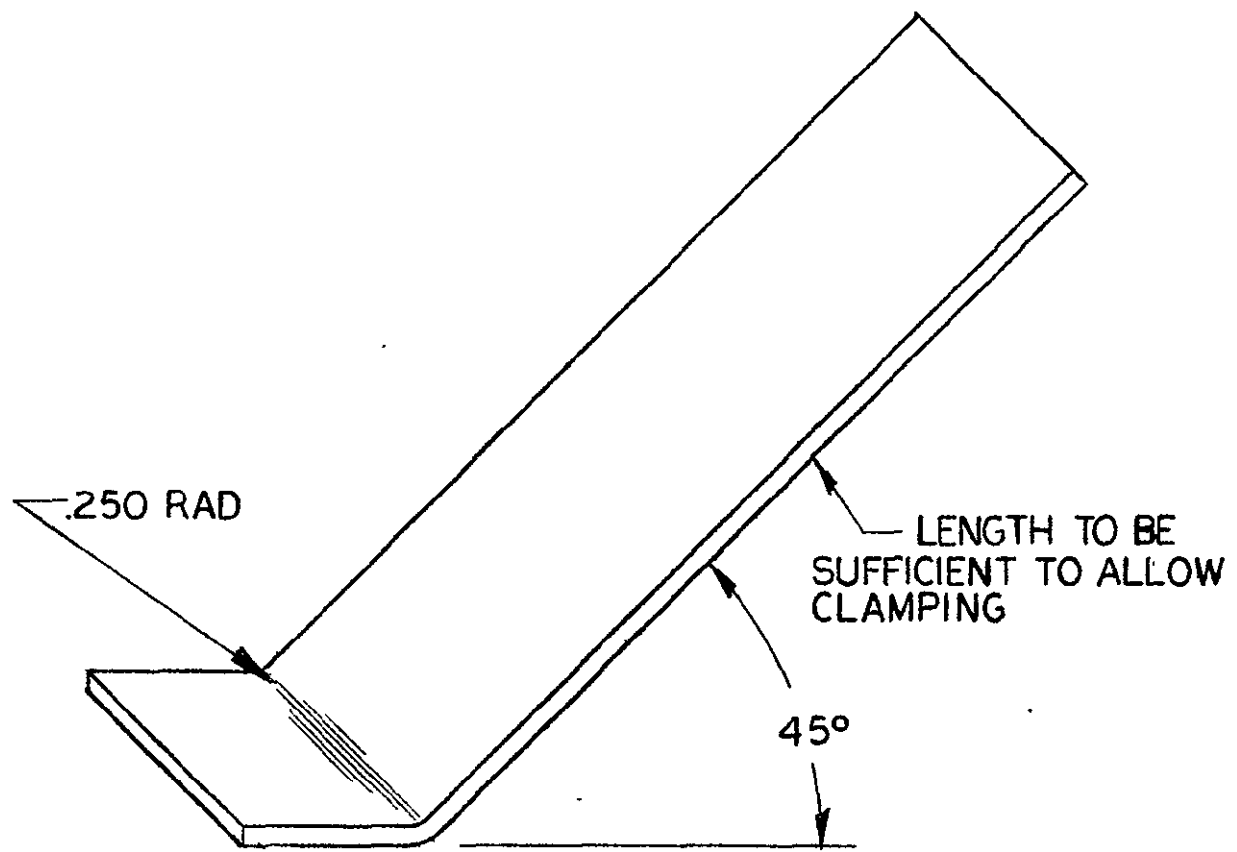
##### 4.6.13.1 Test procedure

a. Pull tabs shall be soldered or welded according to 4.6.12.1 or 4.6.12.2.

b. The cell shall be clamped in the pull tester, which may be a Model 6-092-01 pull tester manufactured by Unitek Corporation, Monrovia, California. The tabs shall be bent up 45 degrees and clamped. The pull force shall be applied to the tabs at an angle of 45 degrees to the face of the cell (the angle enclosed by the two legs of the tab is 135 degrees).

c. The reading of the pull force indicator, which may be a Model 7-015-01 Chatillon gage, shall be recorded at the instant of separation of the tab from the cell.

4.6.14 Spectral response. The short circuit current of the assembly shall be measured under the conditions of 4.6.7.3 and recorded. The assembly



ALL DIMENSIONS IN MM.

FIGURE 2  
CONTACT PULL TAB

shall then be measured with a Corning CS-2-60 filter placed between the unit and the light source. The value of short circuit current obtained in this manner will be recorded.

## 5.0 PREPARATION FOR DELIVERY

5.1 Preservation and Packaging. The assemblies shall be shipped in containers of a design approved by the procuring activity. The containers shall have adequate protective packing materials to prevent damage or shock of the assemblies. Each container shall be heat-sealed in an airtight, water-vapor-proof barrier bag of material in accordance with MIL-F-22191, together with sufficient bagged, activated, dry desiccant in accordance with MIL-D-3464D to prevent atmospheric or other contamination of the surface of the assemblies.

a. One unit of dry desiccants is required for each 90 square inches of bag area (one side only). This material shall not adversely affect the mechanical or electrical properties of the assemblies and shall not come into immediate contact with them.

b. A card-type humidity indicator scaled to 10 to 80 percent relative humidity shall be placed within each sealed bag in an easily viewed location. Containers with visual damage shall be rejected. The reading displayed by the visual humidity indicator card shall be recorded at the time of acceptance. In the event that the humidity indicator shows a humidity level greater than 35 percent, the units shall be rejected and the assemblies re-packaged.

c. Any packing material used shall not affect the mechanical or electrical properties of the assemblies and shall not contaminate the surface of the assemblies. The packaging method shall be approved by the procuring activity.

5.2 Marking of Shipping Containers. Each container shall be clearly identified by the following :

- a. Manufacturer's name and specification number
- b. Shipping lot number and quantity of assemblies.
- c. Month and year of manufacture
- d. Cell current measured at a specified voltage. Current to be in current groups as given in the applicable specification sheet.

5.3 Deliverable Documents. Each shipment of assemblies shall be accompanied by complete major inspection records of all examinations and tests as specified in Section 4 pertaining to the lot from which the cell shipment is made.



## APPENDIX B

SOLAR CELL STANDARDIZATION

COST EFFECTIVENESS

IMPACT ASSESSMENT

FINAL SUMMARY REPORT

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## SOLAR CELL STANDARDIZATION

### I INTRODUCTION

Space solar cells have traditionally been specified by users and procuring agencies on the basis of each mission and satellite configuration. This has resulted in a multiplicity of solar cell types and specifications. It has raised the question of the possible benefits which might result from standardizing solar cells. Spectrolab, Inc. has gathered extensive background material on contemporary technical specifications under contract from NASA.

This study employed the technical material on solar cell specifications and standards developed in the Spectrolab study. In addition, this study contains additional material obtained from many sources in the space solar cell industry and in the spacecraft industry. This report is a summary of the data and analysis in the study. It contains conclusions and opinions of the study team; these are so identified in the text wherever they are not supported by fact or reference.

The methodology was threefold. The existing data was reviewed, including the results to date of the Spectrolab study. Plant visits and interviews were conducted with the space solar cell manufacturers, several spacecraft manufacturers, custom semiconductor device manufacturers, and government technical experts. In the early stages of the study we had difficulty in evaluation and assessment of the data. We concluded that this was for two reasons: First, some sources submitted information that tended to be "self serving;" information that would tend to favor their organization. Second, a substantial fraction of the desired information is subjective. This is particularly true of such things as "workmanship," "appearance," and some of the in-process tests. In the final analysis we gained confidence in the distinction between factual data and subjective opinion. The final step in the methodology was application of economic, business, and technical analysis of the refined information.

There were several important aspects of the space solar cell market and technology that are outside of the scope of this study, for example several research laboratories have promising preliminary results on more efficient cells. We have noted the importance of technological evolution and encourage further study in this direction, but this and related topics are not part of this report.

The initial objective of this study was to determine cost effectiveness and economic impact of the establishment of standards for solar cells. In brief, we found that there were several other related, and more important aspects to the economic and technical questions that were raised. These are related to the size and nature of the market. These considerations were found to dominate the consequences of solar cell standardization. For example, we found that there are nearly 30 different solar cell configurations and specifications in recent use--a distinct trend away from standardization.

Also we found that the participants in the market, suppliers and users, are a very small number of firms (for the bulk of the space cells produced and used). Most of these companies perceive standardization as a risk to their current market position; not a single company saw standardization as a means of increasing its market share.

In this brief report the principle aspects of standardization are discussed. These are compared with the economic nature and structure of the space solar cell industry. Some significant conclusions based on this analysis are presented.

## II STANDARDIZATION

In the Spectrolab survey some 28 industrial and government organizations were asked to reply to detailed questions on a typical specification (based on MIL-C-83443). Their results illustrated a marked difference in acceptable expectations for standardization between government and industrial organizations. Government agencies expected to achieve ease of procurement and common standards, but with little, if any, cost reduction of the cells. Industry expected substantial reduction in the price of cells if they were to support standardization with enthusiasm. (Up to 200% cost reduction according to the Spectrolab results.)

Almost all organizations responding agreed that the "baseline" specification was too confusing. There was difference of opinion, however, over which parts needed revision.

The survey found common opinion regarding some "obstacles to standardization." These included: loss of competitive advantage, overdesign for some missions, and inhibit development of better cells. These concerns were based on concerns by technical evaluators, but we will see later that they seem to stem also from economic considerations.

There is no doubt that some economy can be achieved by reduction in testing and the sacrificial destruction of cells to prove qualification which could result from the establishment of standards. The basic question to be answered is whether the primary and higher order benefits of standardization are positive in the total. It will be seen later that there is some doubt.

Discussion of solar cell standardization has been going on for more than a decade. Little progress has been made. During the last fifteen years, certain cell parameters of significance have evolved as the technology improved, but there has been no general agreement on basic solar cell standards. There are now more than thirty solar cell types and configurations that have been in recent use. Furthermore, because of the uses and applications in spacecraft, it is unlikely that one or two standard solar cells would serve the needs of all users and applications. If, however, there were only a few standard types available, most solar power engineers would work around the handicaps imposed by lack of flexibility of solar cell types.

One of the fundamental questions asked in the work statement for this survey was "Can standardization offer cost savings and, if so, how much?" Existing cost data shows that standardization can realize cost savings on a per cell basis. (This may not be true when viewed from a spacecraft or mission perspective.) Quantity purchases of solar cells vary from about \$5.00 to \$9.00 per cell (2 x 2 cells). The variation in price results from stricter specifications, higher efficiency, additional testing, etc. The additional requirements lower yield, increase direct labor (for testing), and induce the manufacturer to add contingency for uncertainty in yield. Thus, some reduction in the price of the high priced cells could be expected from standardization. Probably no price reduction would result from standardization of low price cells. (It will be seen later that an increase in production volume is the most significant factor in cost reduction. Standardization is not expected to result in increased consumption. Solar cell consumption is not expected to change in the next many years, hence price reductions for this reason are not expected.)

Solar cells consist of (1) direct materials and labor, (2) indirect costs, strongly influenced by yield and volume, and (3) testing. This crude model suggests that the greatest cost reduction can be expected in the low volume, high priced cells by establishing standards. Cost reductions can only be expected on repetitive purchasing of the higher priced cells to the same specification.

There is a significant division of opinion regarding in-process testing and process control procedures. On one hand it is argued that the cell manufacturer will control his process in order to maximize his yield, also it is said that the user is unable to properly monitor in-process procedures either through lack of knowledge or lack of adequate surveillance. Hence, specification of in-process testing and process controls contributes a needless expense. However, we were repeatedly told by cell users that in-process specifications were one of the few ways they had "to keep the vendor honest." It is the tentative conclusion of this study that little cost advantage can be achieved by establishing in-process inspection or test procedures different from those in use now.

It is clear that contact tests are expensive to conduct and they result in the destruction of a significant number of test cells. There seems to be some merit in attempting to establish standard contact tests that would become familiar to the vendors. Also, nondestructive screening tests may have promise; one vendor told us that he relied upon tape pull tests to identify poor contacts before final test. Good contacts are very important to the user. A defective lot can be expensive to rework if many of the cells have gotten into the assembly process. Thus, it seems that it would be desirable to look further into standardization of contact testing.

In summary, we found no insurmountable obstacle to standardization, at least from a technical point of view. On the other hand, there does not seem to be any compelling reason for standardization to be supported by the industry. No one in industry identified a clear cut technical reason for standardization. Consequently, it is our opinion that standards will not be adopted spontaneously by the industry.

### III ECONOMIC ANALYSIS

In our study we found that economic analysis of the space solar cell industry was an important factor of the question of standardization. An understanding of the economic aspects will give you perspective in evaluating what can be reasonably expected for producers in the industry. Also, standardization can be expected to have important second and third order effects on the producers and users.

#### A. Structure of the Industry

The space solar cell industry can be characterized by what economists call a "near duopoly." (A duopoly is an industry consisting of only two firms.) The industry consists of Spectrolab Inc. and the Photovoltaic Division of Optical Coating Laboratories, Inc. (OCLI). These companies roughly split the market; Spectrolab has 60-70% and OCLI has 30-40%. Other companies have the technical capability to make space solar cells, but choose to supply the terrestrial market at this time. There are only two suppliers of space cells at this time for all practical purposes.

The current solar cell suppliers are all small companies, although some have large company affiliations; Spectrolab Inc. is a subsidiary of Hughes, and Mobil-Tyco (Mobil Oil), Sharp, and IBM are making terrestrial cells in small quantities.

The space solar cell market is small, about \$5 million per year, and is not expected to grow. Thus, it is unlikely that the space solar cell market will attract new vendors or investment capital. On the other hand, some solar cell companies, e.g. Solarex regard themselves as potential competitors in the space market. Consequently, the space solar cell industry is extremely concentrated and the producers are burdened with excess capacity.

Let us see what the effect of production output has on unit cost of solar cells, Figure 1. If a firm is producing cells at a rate  $q_b$  then its unit cost is  $C_b$ . If the firm can increase production to  $q_a$ , then its unit cost decreases to  $C_a$ . Thus, a firm will strive to increase production in order to reduce unit cost. If it can achieve the higher production, then it can increase profit or maintain a reasonable profit and be able to reduce selling price.

Now, what are the effects of price reduction on solar cell sales? First, let's look at the total market. The demand for space solar cells is a "derived demand." The demand for solar cells is "derived" from the demand for satellites. But, because solar cells represent a negligible fraction of the cost of a satellite, changes in solar cell price will not affect the demand for satellites. Consequently, solar cell price changes will not change the demand for space solar cells.

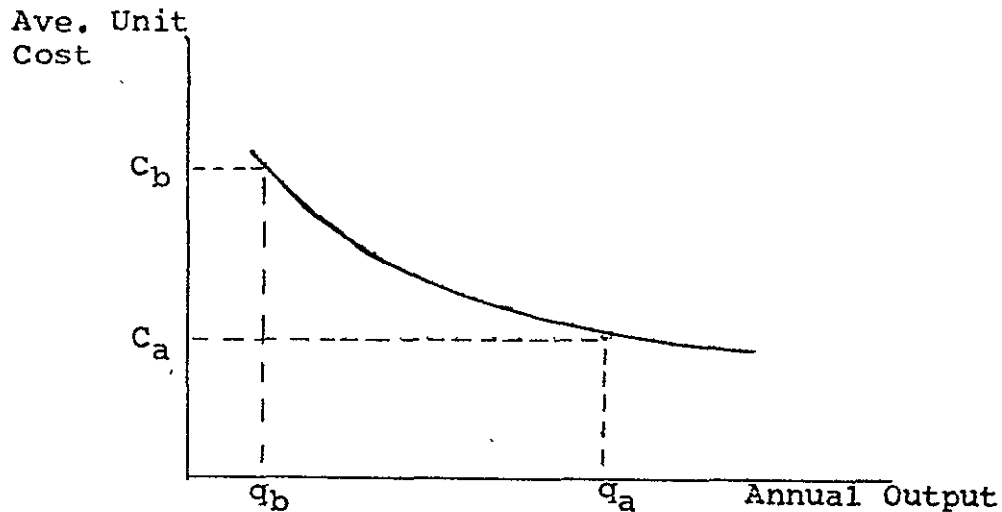


Figure 1: Typical Total Cost Curve for a Firm

The independence between solar cell price and the market demand for solar cells is known as an "inelastic market." In this case it is a result of the derived demand characteristic of the space solar cell market, and the fact that solar cells are such a small fraction of the cost of satellites. In an inelastic market, the demand for the product (solar cells) changes slowly as a function of the price of the product. Thus, there is no incentive to solar cell manufacturers, as a whole, to reduce prices.

Price reduction through standardization is not an incentive to cell manufacturers unless it assures vendors a price reduction. We have seen earlier that this is not likely. On the other hand, in view of the inelastic market, over capacity of suppliers, and absence of market growth; there are incentives to increase prices. One way to do this - in the present market structure - is emphasis of custom features, quality, efficiency, etc. Each of the suppliers competes on a performance basis rather than a cost basis. This tends to justify each supplier's attempt to raise price as much as possible. This is a distinct incentive against standardization.

Remember that this space solar cell industry is characterized by:

- 1) an inelastic market
- 2) a small market (\$5M) with no growth
- 3) two suppliers - a duopoly.

## B. Intra-Industry Structure

Each of the cell manufacturers finds himself facing intra-industry competition as the major market force in this duopoly. If a vendor seeks to achieve market dominance by price cutting, he "spoils" the market for himself and his competitor. On the other hand, if he is not competitive in price and service, he loses his share of the market. Thus, each producer must operate with both short term methods and long term strategies--and these may be different. For example, one vendor may cut price in the short run to: (1) protect his market share, (2) fill in a period of slack demand, (3) induce a rival to obtain a contract at an unfavorable price in the hope that future prices may be more attractive.

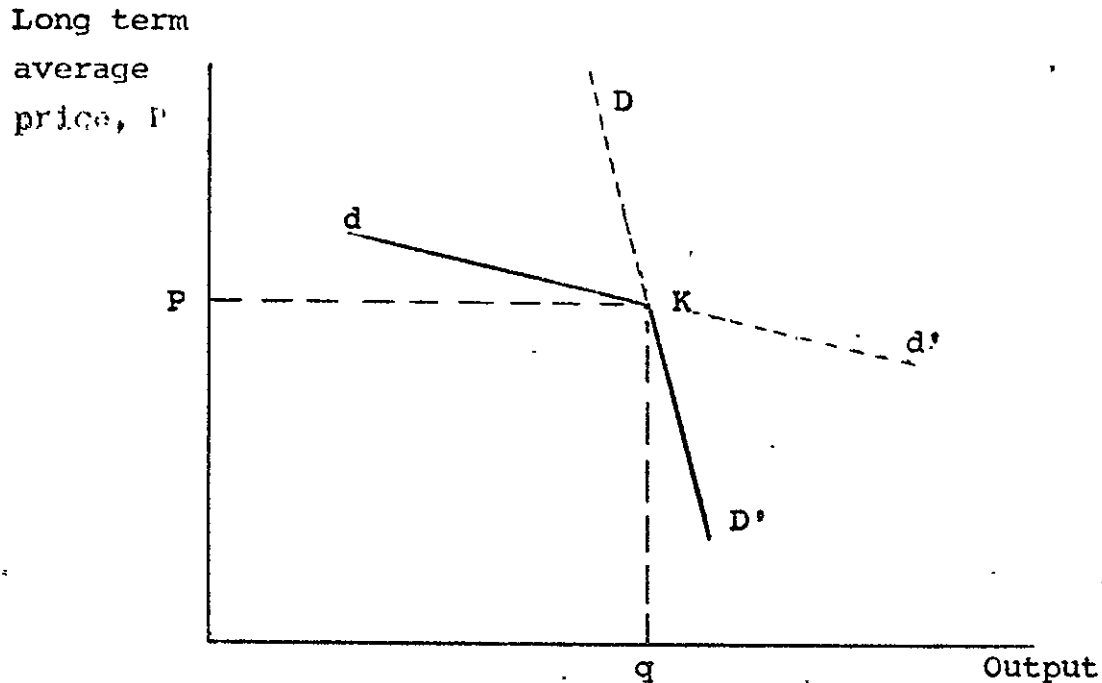
The duopoly works both ways. Investigation showed that most users tended to stay with the same supplier. The users were content with the knowledge of the existence of a qualified second source. With this assurance, the users exerted pressure for better efficiency and reliability at a lower price. Thus, the users exploited the duopolistic market structure to increase intra-industry competition. In view of the intense competition in the satellite market, and the small number of competitors, this is not surprising. Emphasis has been placed on cell performance and price by each satellite manufacturer in each competition, because they all compete in a fluid market with changing technology. Thus, the cell manufacturer frequently finds it to his advantage to emphasize performance rather than cost in the early stages of competition and bid negotiation. These are short term intra-industry factors.

In the long term, the space solar cell industry is characterized by relatively stable prices. This can be explained by a "kinked demand curve" (Figure 2). Any firm in the industry can be viewed as facing two distinct demand curves. The first demand curve,  $D-D'$ , describes the demand facing an individual firm if all firms in the industry match its price changes. This fairly inelastic demand curve is sometimes called the "industry demand curve." The second curve,  $d-d'$ , is more elastic (less sloped), it describes the demand facing the firm if the rival firm holds prices fixed when the first firm changes its price. This second curve is sometimes called the "firm's demand curve."

Consider the situation that exists in the space solar cell industry. The industry is characterized by inelastic demand. The total industry market potential is fixed and cannot be readily expanded. Also firms in the industry are plagued by chronic excess capacity and frequent periods of slack demand.

Attempts at long-term price reductions, therefore, will possibly stimulate an industry-wide price war, i.e., rival producers will tend to follow a long-term price cut rather than incur sizeable losses in their market share. But, on the other hand, no rival will follow a long term price rise because this action will permit the competitor to exercise the option of underbidding the firm which raised the price, and expand its market share at the expense of the firm maintaining the higher price.





This means that the demand curve for an individual firm is the industry curve,  $D-D'$ , which is applicable from  $K$  to  $D'$  for downward price changes from  $P$ . But the firm's demand curve is applicable from  $K$  to  $d$  for upward price changes from  $P$ . The important point is that there is little incentive for firms to change their long term average price from  $P$  if it is earning an acceptable rate of return on capital. Prices will tend to be rather rigid at  $P$ .

### C. Profitability of Solar Cell Manufacturing

Small, specialty semiconductor companies have many similarities. They typically are labor intensive and capital intensive. Most of them are making products for a limited market and are not very profitable. Let us examine the profitability of a contemporary space solar cell company with these assumptions.

The following factors are typical for solar cell manufacturing and for custom, low volume, semiconductor manufacturing:

- 1) overhead 200%
- 2) general & administrative 20%
- 3) the finished product is comprised of:
  - labor 70%
  - material 30%

- 4) the company has a capacity for \$6 million in annual sales
- 5) the company has an original investment of \$1.5 million in capital equipment
- 6) the company has  $\frac{1}{2}$  million per year of fixed overhead (DI water, electricity for furnaces, etc.)

Under these conditions this hypothetical company can earn a profit of about 5% on sales of \$3 million of solar cells at current prices. If this company can achieve sales of \$6 million at the same prices, it will make a profit of about 15%. But, if sales slip to \$2 million, then the company becomes unprofitable with a loss of 5%. In order to remain profitable at a reduced sales volume the company has only two choices: cut direct costs, or raise prices (assuming that the fixed overhead cannot be changed in the short term). The kinked demand curve has already indicated the strategy limitations available to the company.

For the current \$5 million per year space solar cell market, the two suppliers could probably do a little better than break even only if they evenly divided the market. However, from several sources it has been determined that this is not the case.

What about the strategic implications for solar cell standardization? One thing is clear! Standardization will not lead to automation of production and consequent large economies of scale. The market simply isn't large enough; and never will be even in the most optimistic forecasts. In order to justify the use of automatic production methods, the market would have to be at least a factor of ten larger in dollars. This would mean a solar cell market that is a factor of 20 to 30 larger in solar cells. Or 20 to 30 times larger in the number of satellites. It just doesn't seem that this will happen.

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Historical price data shows that significant price reduction of solar cells has occurred during the last 5 to 6 years. The economic analysis indicates that has happened at the expense of the producers under the competitive pressure of the kinked demand curve. It has not resulted from any significant economies of production as determined from the investigations leading up to this report. Furthermore, it is important to realize that standardization has not contributed to price reduction.

Future standardization of space solar cells can be expected to have little effect on prices of solar cells, except where such standardization can be shown to have a direct contribution to the labor content of the finished cell. If the elements of standardization do not reduce direct labor required to produce the cell, then no price reduction should be expected. We found, in the course of this study, that there is little reason to expect improvements in yield to result in price reduction. Efforts to standardize in order to improve yield are not likely to be fruitful. Also, it has been shown that the market is too small to achieve price reduction through automation of production, therefore, efforts to standardize for application of automatic production methods are not going to be successful in

achieving cost reduction or in achieving the use of automated production methods.

Finally, there was a frequently voiced concern that standardization might impede technological improvements of solar cells. Although it is not possible to quantify this factor, it should be borne in mind in formulating cell standards.

Thus, it appears that extensive standardization of cells is not desirable from an economic view or from an industry view. Selective applications of standards may be of significant technical value. Also selection of standards that will permit the reduction of direct labor in production, or in testing, may have some limited effect in price reduction. At the present market size, however, the controlling factor on standardization is economic. It has been shown that there are no economic incentives in the space solar cell industry to encourage standardization. In fact, the opposite is true. The economic elements are such that the cell manufacturers must perceive that standardization does not improve their economic situation. The same thing may also be true for the satellite manufacturers, but this was not investigated in the course of this study.